High Precision Solar Neutrino Spectroscopy with Borexino and JUNO

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PhD Defense
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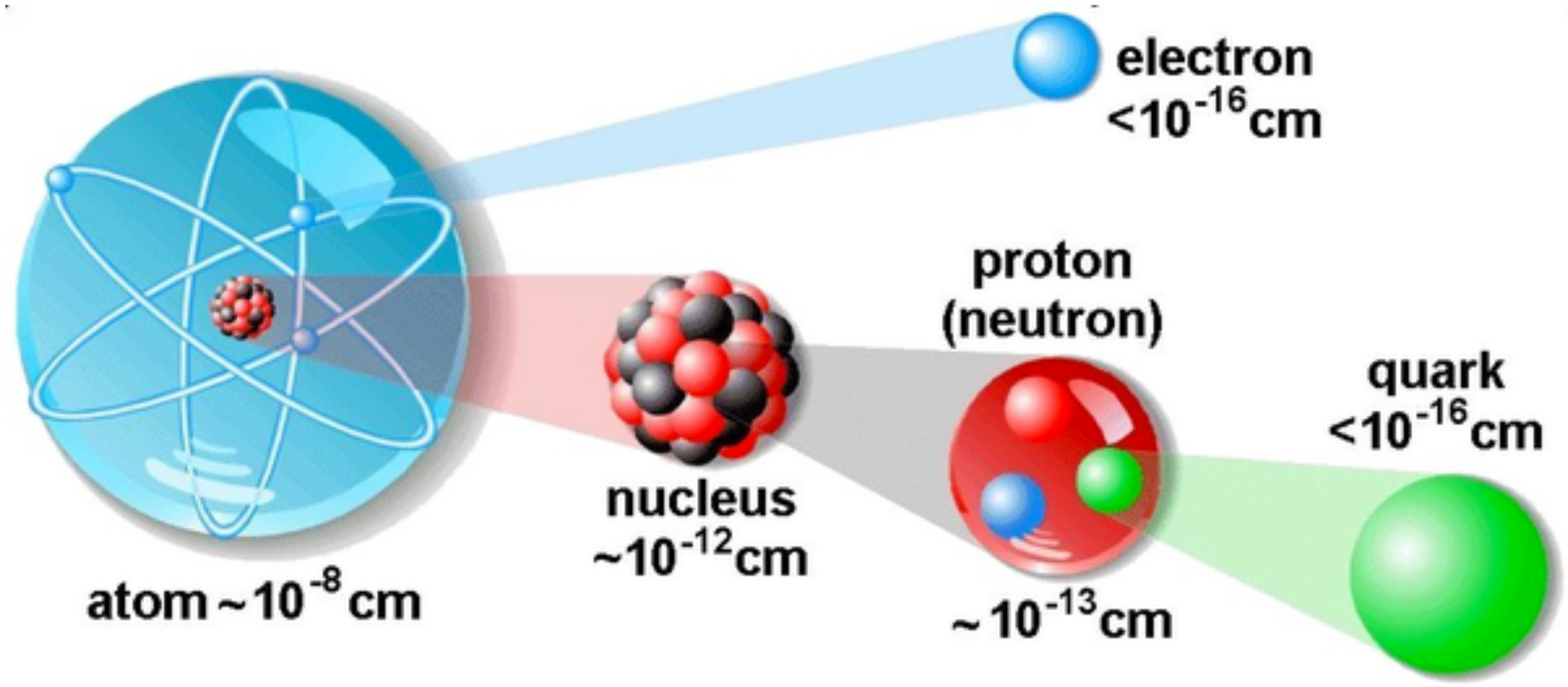
Outline

- Why solar neutrinos?
- High precision measurements with Borexino
- Potential of JUNO
- Future: CNO solar neutrinos
- Conclusions

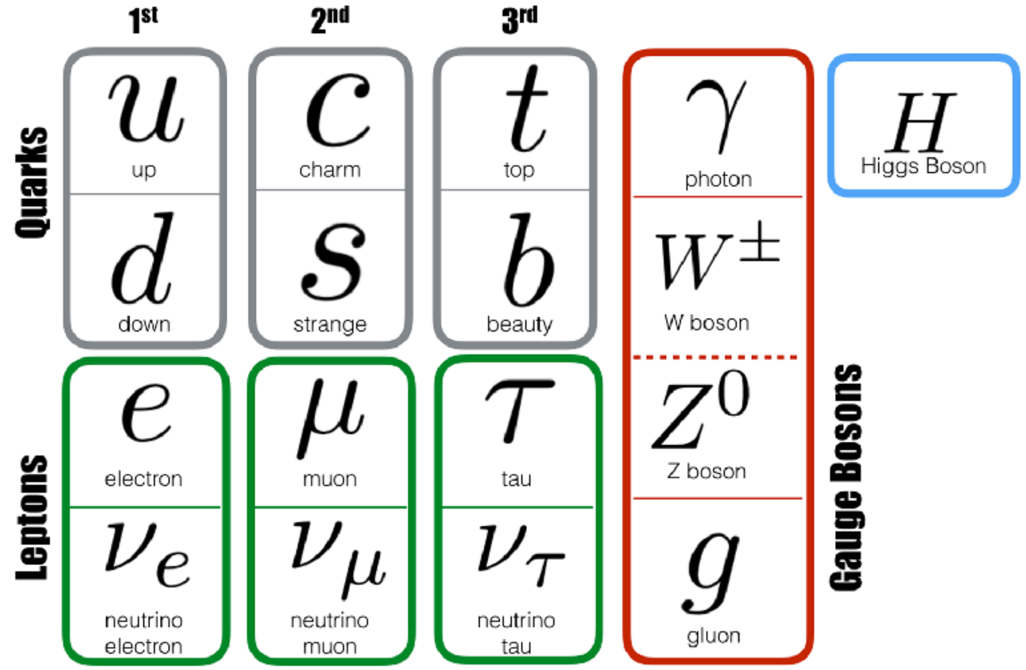
Why Solar Neutrinos?

Since Greek time we know that..

- The world is made of atoms
- And atom is made of more fundamental particles



https://www.quora.com/What-size-are-the-particles-of-an-atom-in-relation-to-its-size



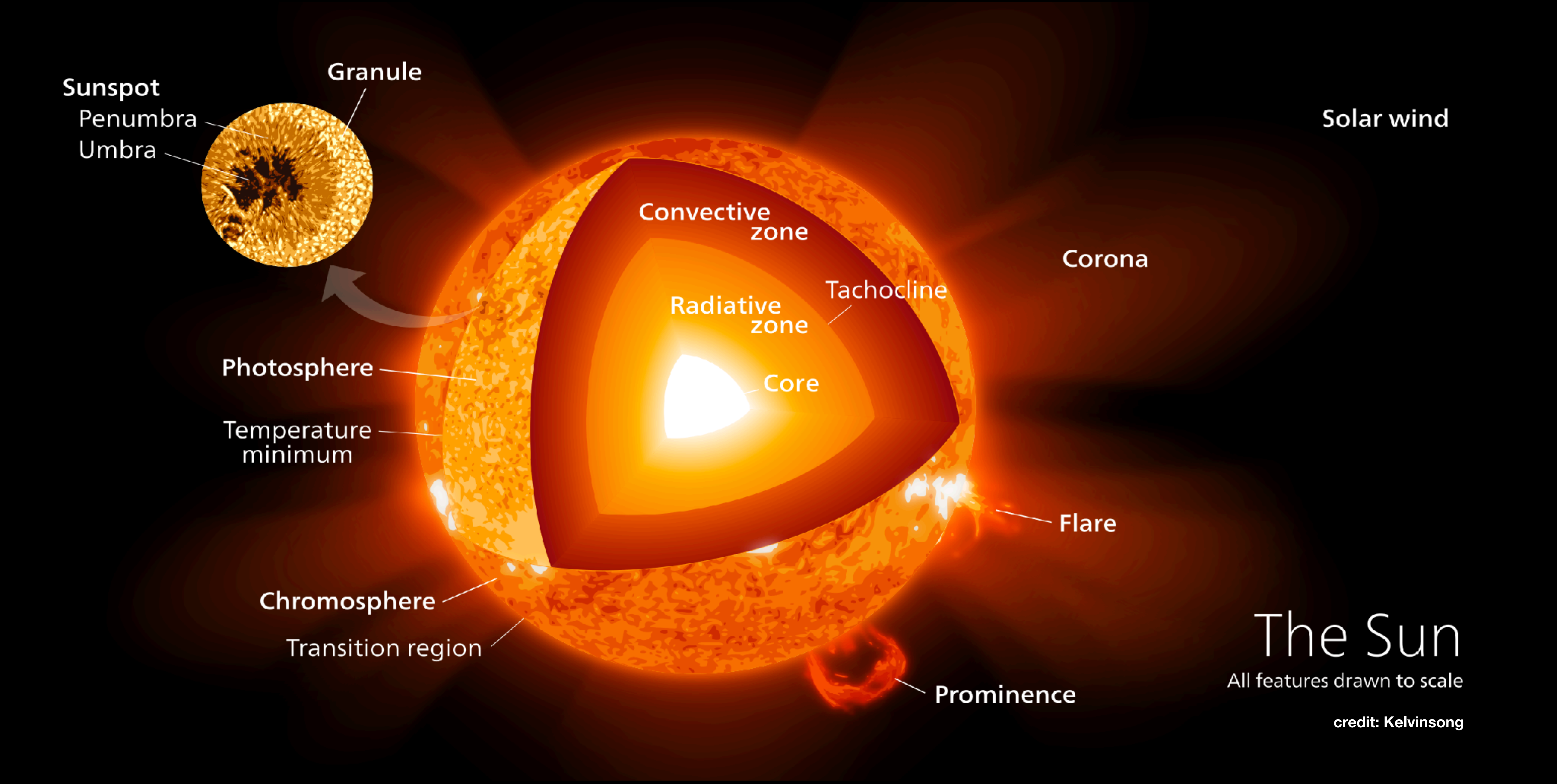
http://www.physik.uzh.ch/en/researcharea/lhcb/outreach/StandardModel.html

And..

Neutrinos are one (three) of these particles

The Sun: a source of photons and ν

By eye we can only see the chromosphere. With neutrinos we see the core



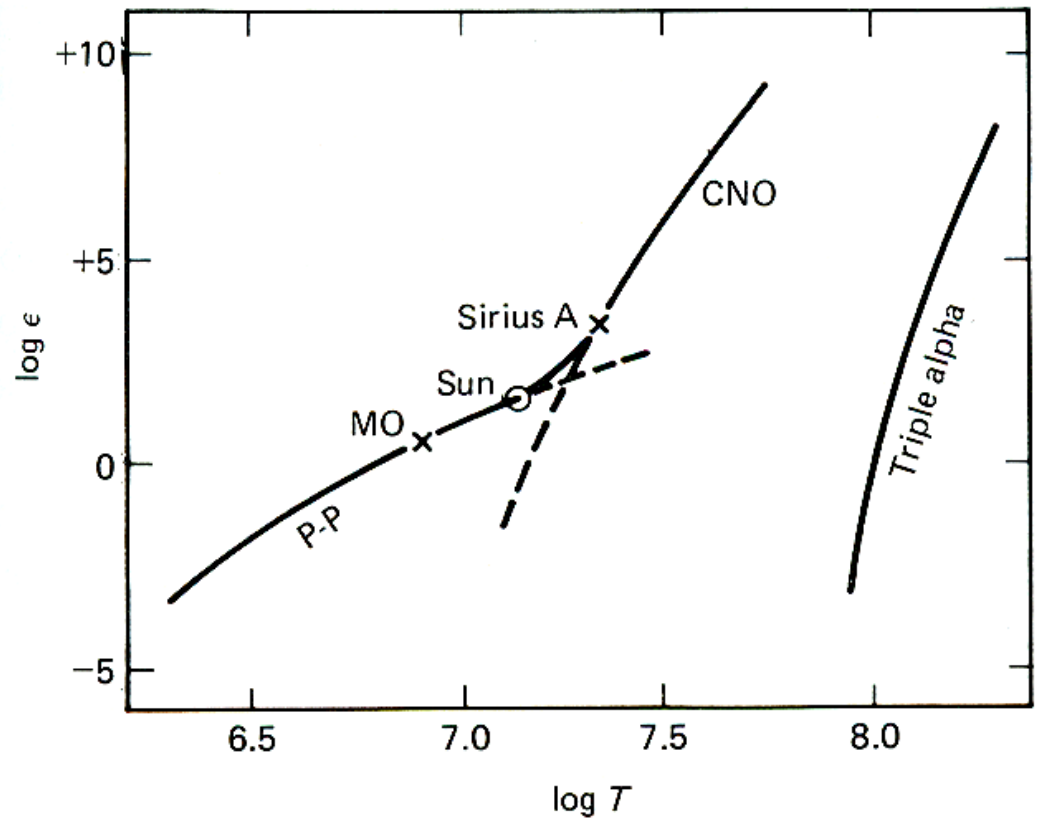
credit: Kelvinsong

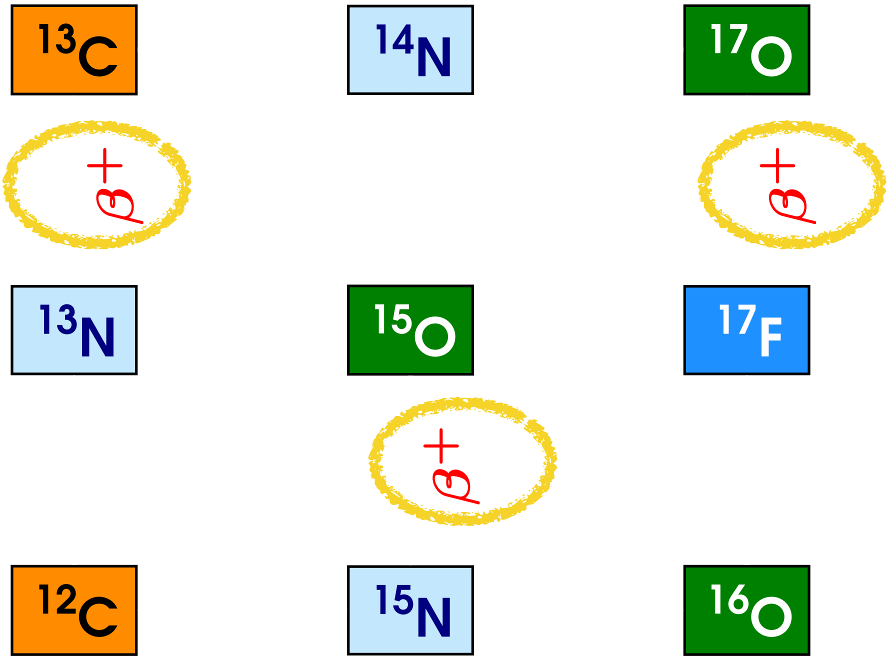
ν_e

ν_e

ν_e

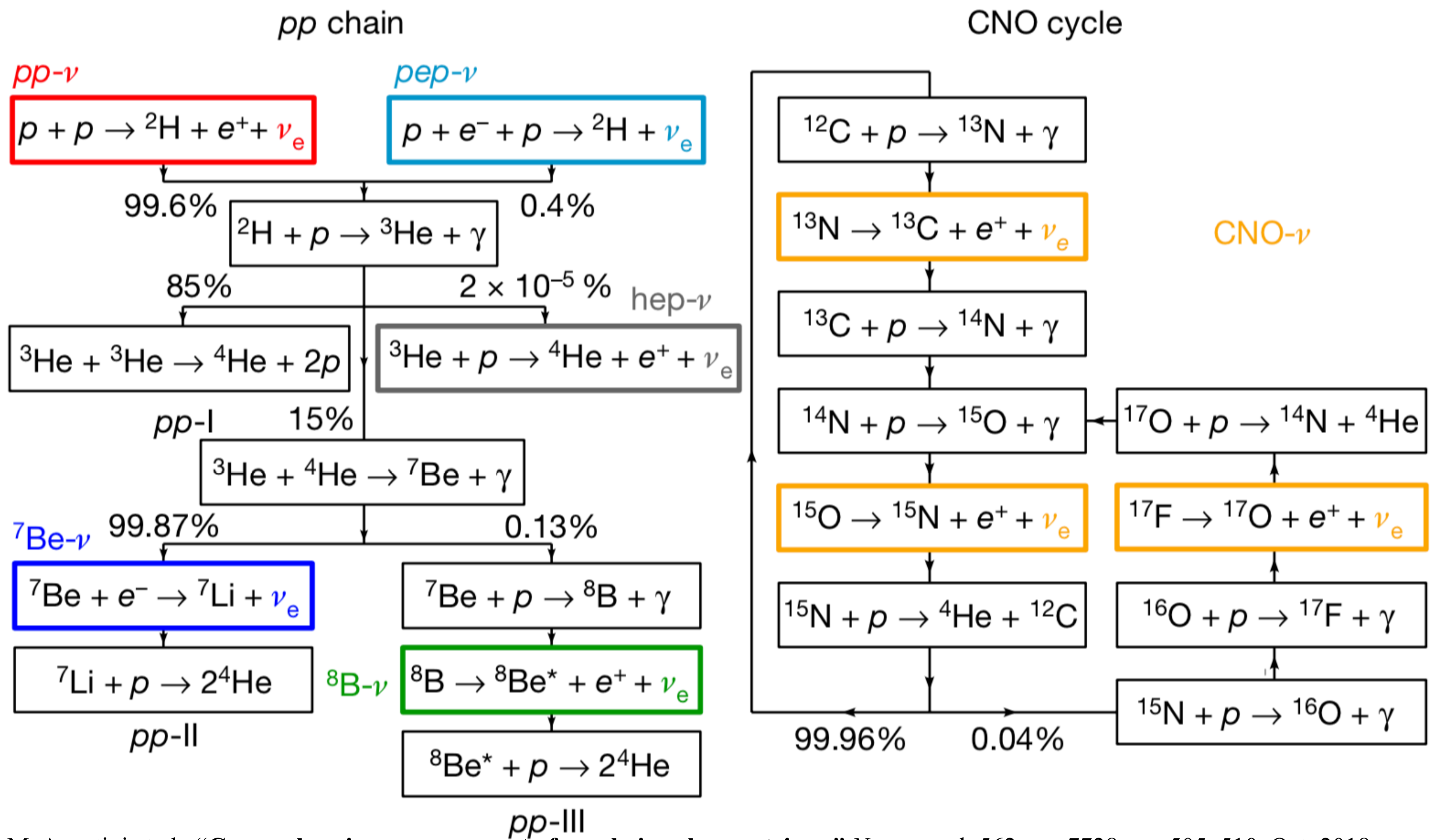
^{8}B





Solar Neutrinos come from fusions

- Two ways of pp-fusion (4p -> ^{4}He + 26.73 MeV)
    - pp-chain: Sequential reactions (~99% for the Sun)
    - CNO-cycle: C,N,O as catalysts (important for heavy/late stage stars)



pp chain

pp-ν: $p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$

pep-ν: $p + e^{-} + p \rightarrow {}^{2}\mathrm{H} + \nu_e$

99.6% 0.4%

${}^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \gamma$

85% 2×10^{-5} % hep-ν

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$

${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \nu_e$

pp-I 15%

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

^{7}Be-ν 99.87% 0.13%

${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$

${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{7}\mathrm{Li} + p \rightarrow 2\,{}^{4}\mathrm{He}$

^{8}B-ν: ${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$

pp-II

${}^{8}\mathrm{Be}^{*} + p \rightarrow 2\,{}^{4}\mathrm{He}$

pp-III

CNO cycle

${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$

${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$

CNO-ν

${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$

${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$

${}^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$

${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$

${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^{+} + \nu_e$

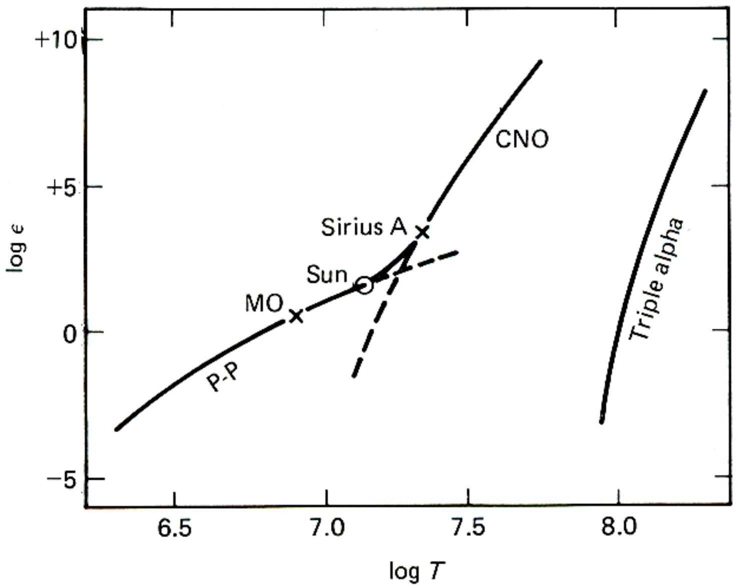
${}^{15}\mathrm{N} + p \rightarrow {}^{4}\mathrm{He} + {}^{12}\mathrm{C}$

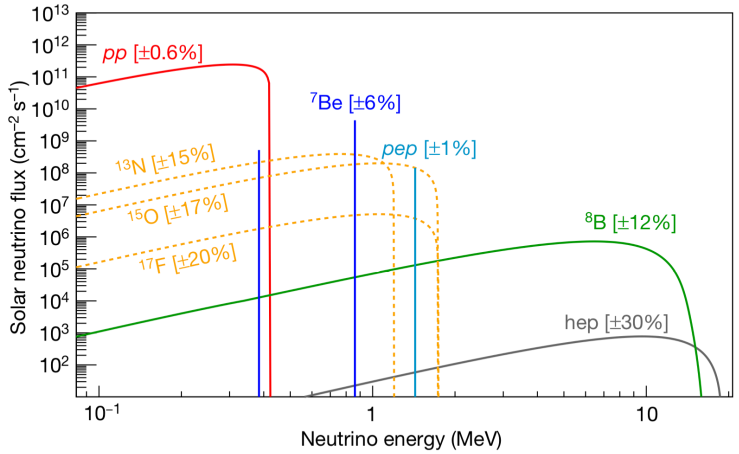
${}^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$

${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$

99.96% 0.04%

https://www2.mps.mpg.de/solar-system-school/lectures/intro_solar_physics/Intro_solar_physics_part1.pdf





M. Agostini et al., “**Comprehensive measurement of pp-chain solar neutrinos**,” *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.

Standard Solar Model (SSM)

- Standard Solar Model (**SSM**): the model of the Sun.
- The Sun is the key reference of cosmology

Input

- solar luminosity Lo=3.844(1 ± 0.4%) 1033 erg/s
- solar radius Ro=6.9598(1± 0.04%) 1010 cm
- photospheric comp. (Z/X)photo=0.0245(1±6%)
- Nuclear physics (cross-sections etc.)

Output

- helium abundance Yphoto= 0.249 (1± 1.4%)
- Rad.->conv. Rb =0.711 (1 ± 0.14%) Ro

Mass conservation

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$$

Energy transport (radiation)

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L}{4\pi r^2}$$

Energy production

$$\frac{dL}{dr} = 4\pi r^2 \rho\varepsilon$$

Uniform at the beginning

Some reference
http://www.astro.caltech.edu/~george/ay1/lec_pdf/Ay1_Lec08.pdf
http://cos.colorado.edu/~kevinf/PAPERS/solmodel.pdf
https://www2.mps.mpg.de/solar-system-school/lectures/intro_solar_physics/Intro_solar_physics_part1.pdf
www.fe.infn.it/~ricci/seminars/trieste_2.ppt

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Uniform at the beginning

←

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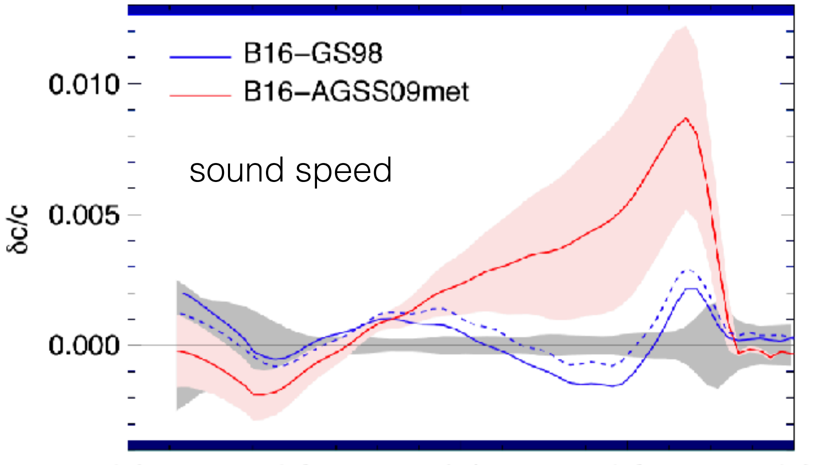
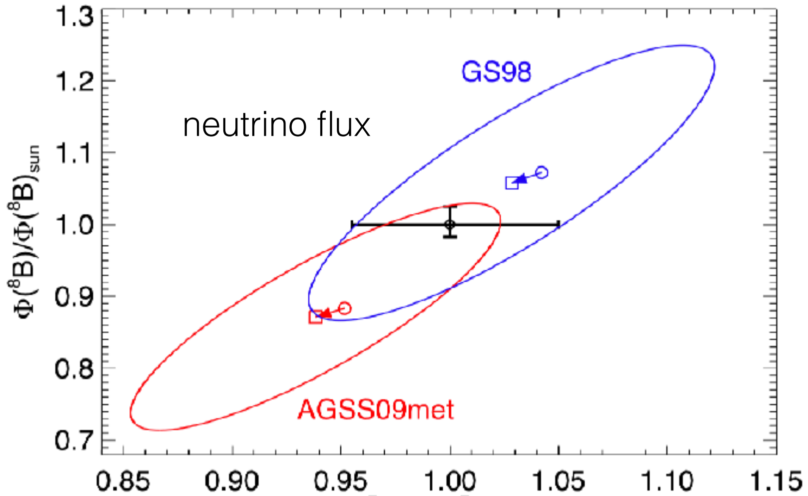
- Rad.->conv. Rb =0.711 (1 ± 0.14%) Ro
- **Neutrino flux?**

Some reference
http://www.astro.caltech.edu/~george/ay1/lec_pdf/Ay1_Lec08.pdf
http://cos.colorado.edu/~kevinf/PAPERS/solmodel.pdf
https://www2.mps.mpg.de/solar-system-school/lectures/intro_solar_physics/Intro_solar_physics_part1.pdf
www.fe.infn.it/~ricci/seminars/trieste_2.ppt

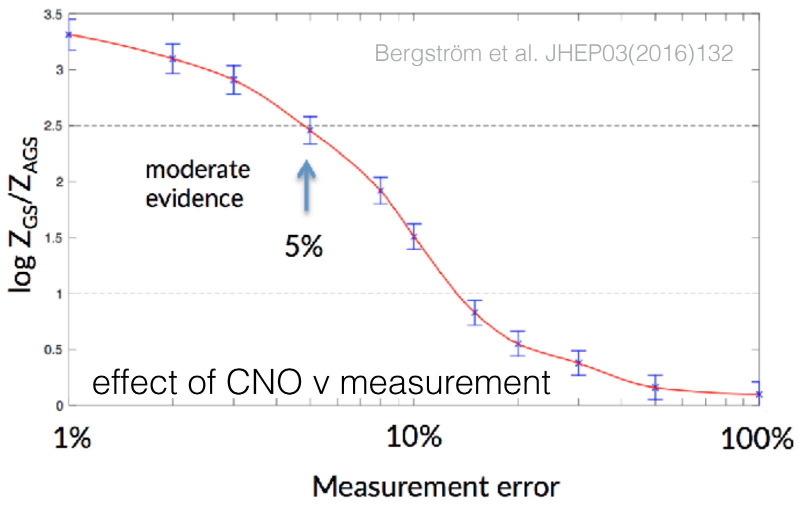
Solar Metallicity Problem



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model



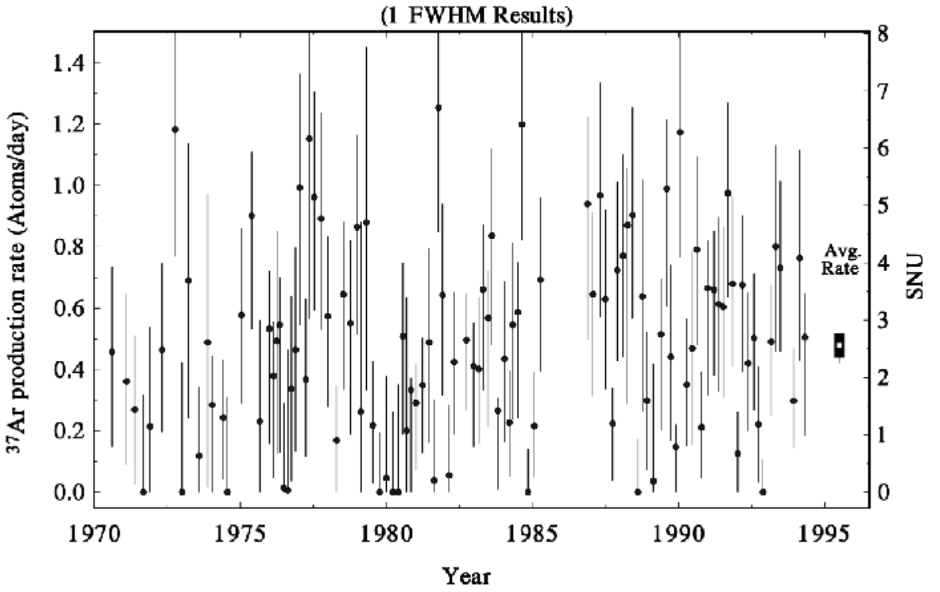
Bergström et al. JHEP03(2016)132

- Two typical Standard Solar Models
  - **GS98**: Higher fraction of “metals”: **HZ**
  - **AGSS09**: **LZ**. Improved, but lost agreement with helioseismology
- Solar neutrino to resolve HZ/LZ
  - pp chain: ^{8}B(SuperK) lies in the exact middle of HZ/LZ
    - BX alone have moderate discrimination power, see later
  - CNO chain: 5% to resolve

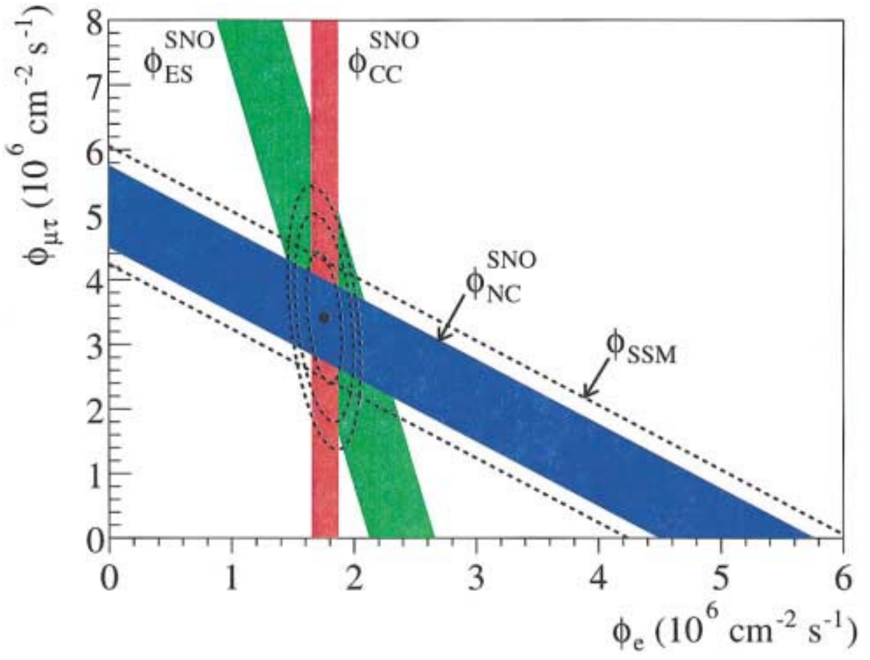
Neutrino Oscillations

- **Experiments see less** incompatibly **less** solar neutrinos than SSM predictions (R Davis et al. PRL 1968)
- It was found that neutrinos are converted to other flavors during propagation, i.e. **neutrino oscillates**. (SNO PRL 2001; Nobel prize in 2015 to Kajita and McDonald)

HomeStake	2.56 ± 0.23
SSM	8.6 ± 1.2



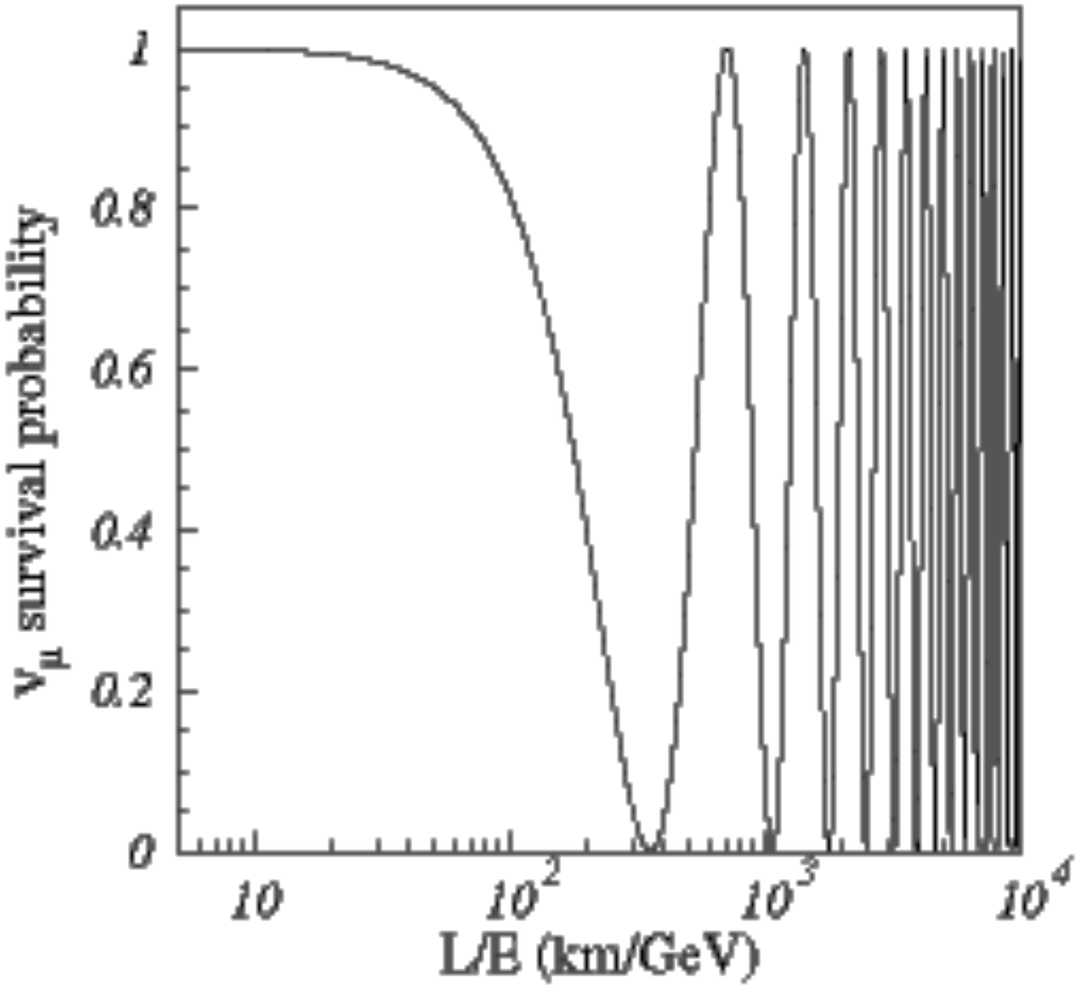
B. T. Cleveland *et al*., "**Measurement of the Solar Electron Neutrino Flux with the Homestake Chlorine Detector,**" *Astrophys. J.*, vol. 496, no. 1, pp. 505–526, 1998



SNO collaboration, "**Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory,**" *Phys. Rev. Lett.*, vol. 89, no. 1, pp. 1–6, 2002.

Neutrino oscillations in Vacuum

- **Neutrino oscillation** is due to **mixing** of mass (**propagation**) eigenstate and flavor (**production**) eigenstate. (Pontecorvo, 1957)



http://antares.in2p3.fr/Overview/particle.html

$$P\left(|\nu_e\rangle \to |\nu_e\rangle\right) = \left|\langle\nu_e|\mathcal{U}(t,0)|\nu_e\rangle\right|^2$$

$$\simeq 1 - \sin^2 2\theta \cdot \sin^2\left[1.27\times 10^3 \cdot \Delta m^2\ (\mathrm{eV}^2)\cdot \frac{L}{E}\ (\mathrm{km/MeV})\right]$$

Figure: how neutrino appear/disappear during propagation

Neutrino oscillations in Matter

- Presence of **matter** (The Sun for solar neutrinos) adds potential to the evolution operator (Hamiltonian) and **changes** the flavor eigenstate and thus **the mixing angle**.

$$\boxed{P^{\text{adiabatic}}_{\nu_e\to\nu_e}(L) = \frac{1}{2} + \frac{1}{2}\cos 2\theta^m_{\text{p}} \cos 2\theta^m_{\text{d}}}$$

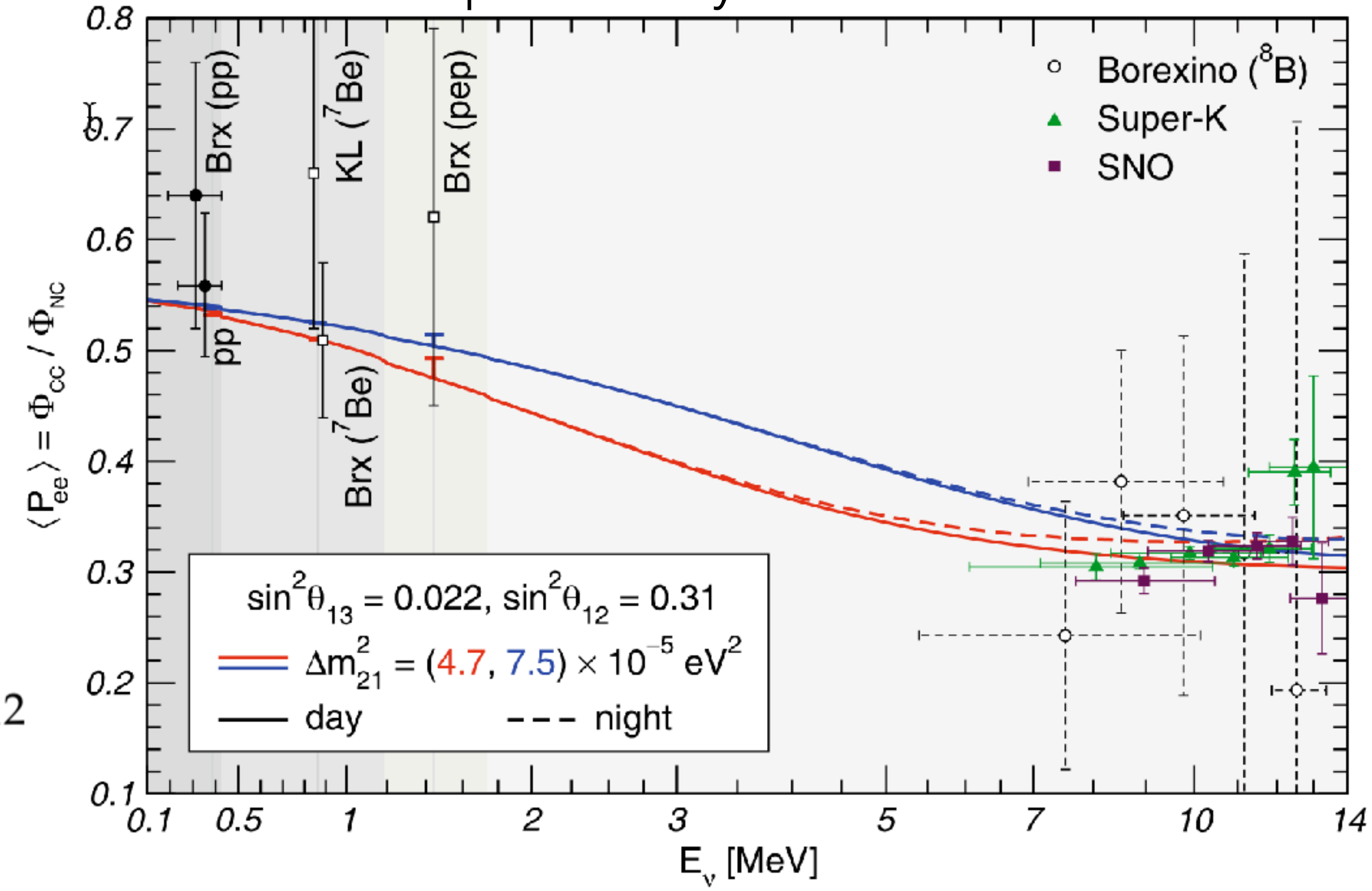
$$\cos 2\theta^m = \frac{\cos 2\theta - \epsilon}{\sqrt{(\cos 2\theta - \epsilon)^2 + (\sin 2\theta)^2}}$$

$$\epsilon = \frac{2 \cdot E_\nu \cdot \sqrt{2} G_F n^{\text{p}}_e}{\Delta m^2}$$

Vacuum regime $\epsilon_{12} \to 0 : \quad \cos 2\theta^m_{12} \to \cos 2\theta_{12}$

Matter regime $\epsilon_{12} \to +\infty : \quad \cos 2\theta^m_{12} \to -1$

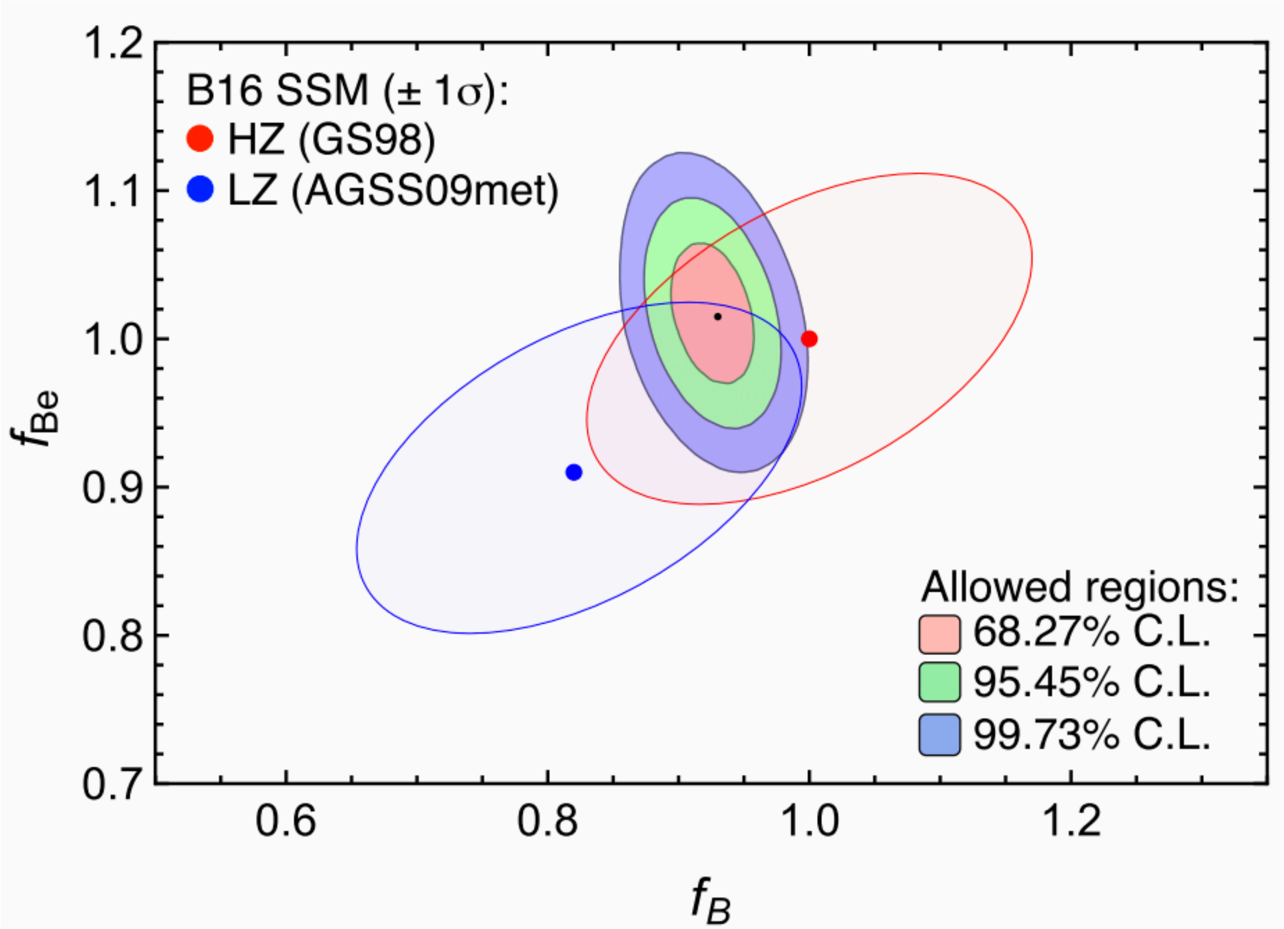
will be updated by Borexino results



M. Maltoni and A. Yu. Smirnov, "**Solar neutrinos and neutrino physics,**" *Eur. Phys. J. A*, vol. 52, no. 4, p. 87, Apr. 2016.

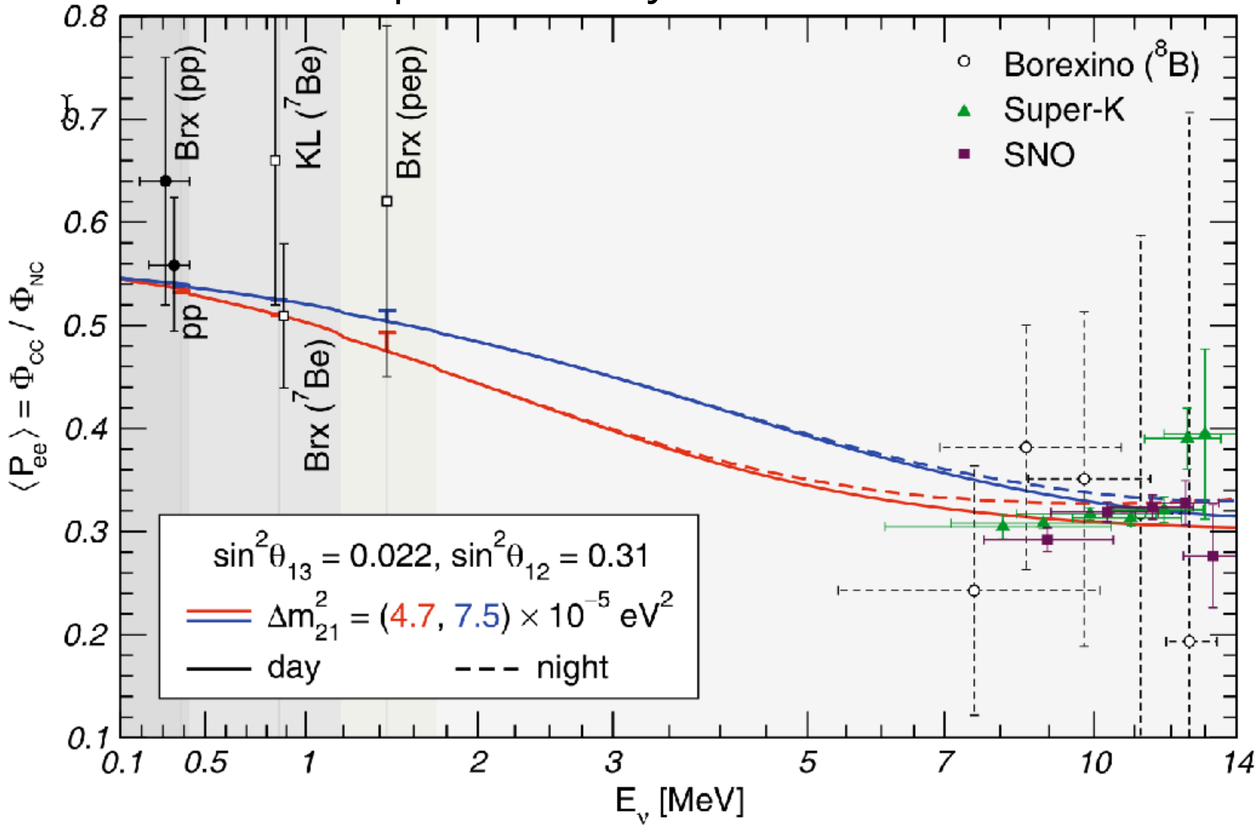
Summary: why solar neutrinos

- A probe of the Sun + a probe to study neutrino oscillation



M. Agostini *et al*., "First Simultaneous Precision Spectroscopy of *pp*, ^{7}Be, and *pep* Solar Neutrinos with Borexino Phase-II," 1707.09279

will be updated by Borexino results



M. Maltoni and A. Yu. Smirnov, "**Solar neutrinos and neutrino physics,**" *Eur. Phys. J. A*, vol. 52, no. 4, p. 87, Apr. 2016.

High precision measurements with Borexino

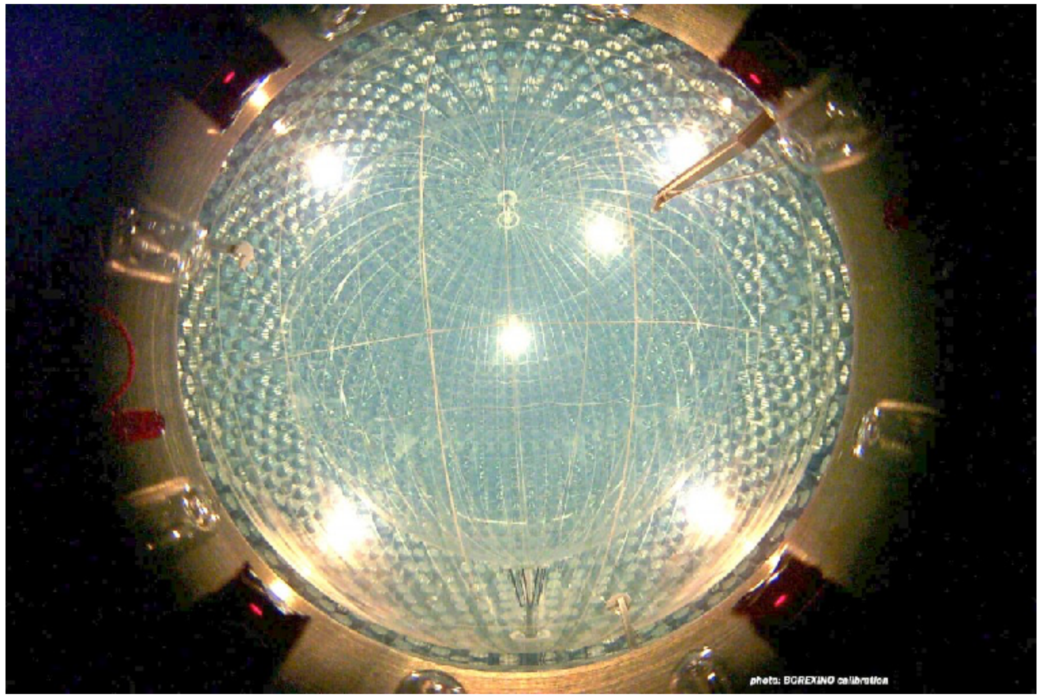
Chapter 4, 5, 6

Table of contents

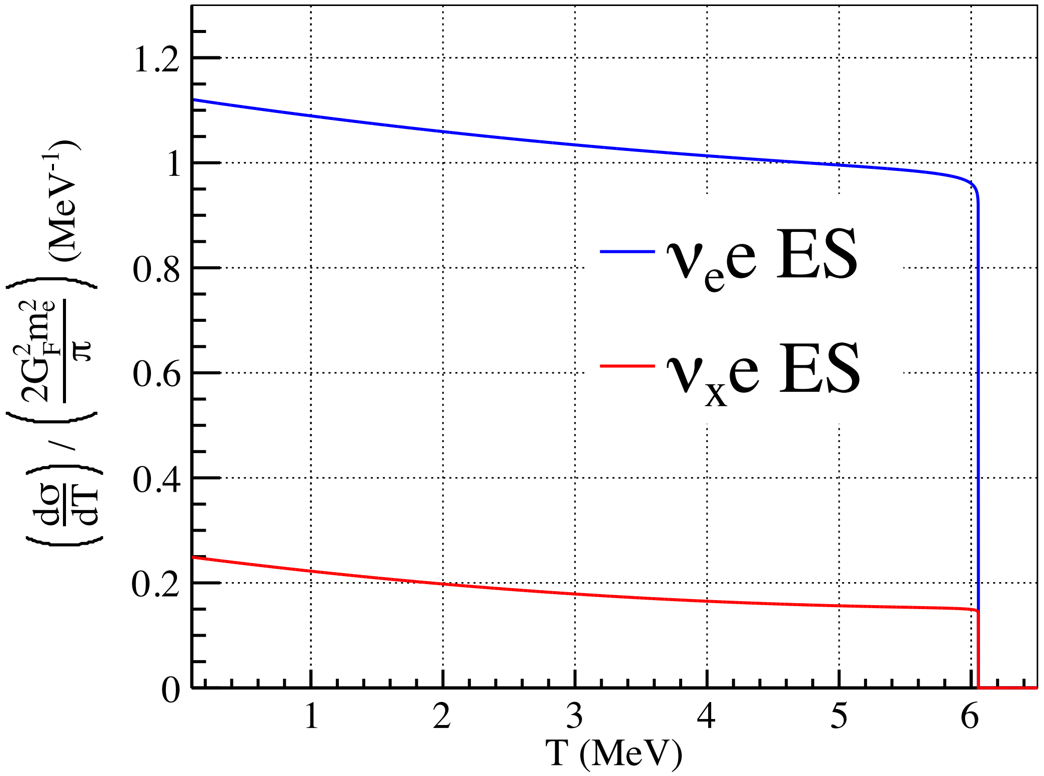
- Borexino detector
- Development of Analytical response function. (ch4)
- GPU fitter + Analytical multivariate method. (ch3)
- Evaluation of systematic uncertainties (ch5)
- Measurement of solar neutrino rates (ch6)

Detection with Borexino

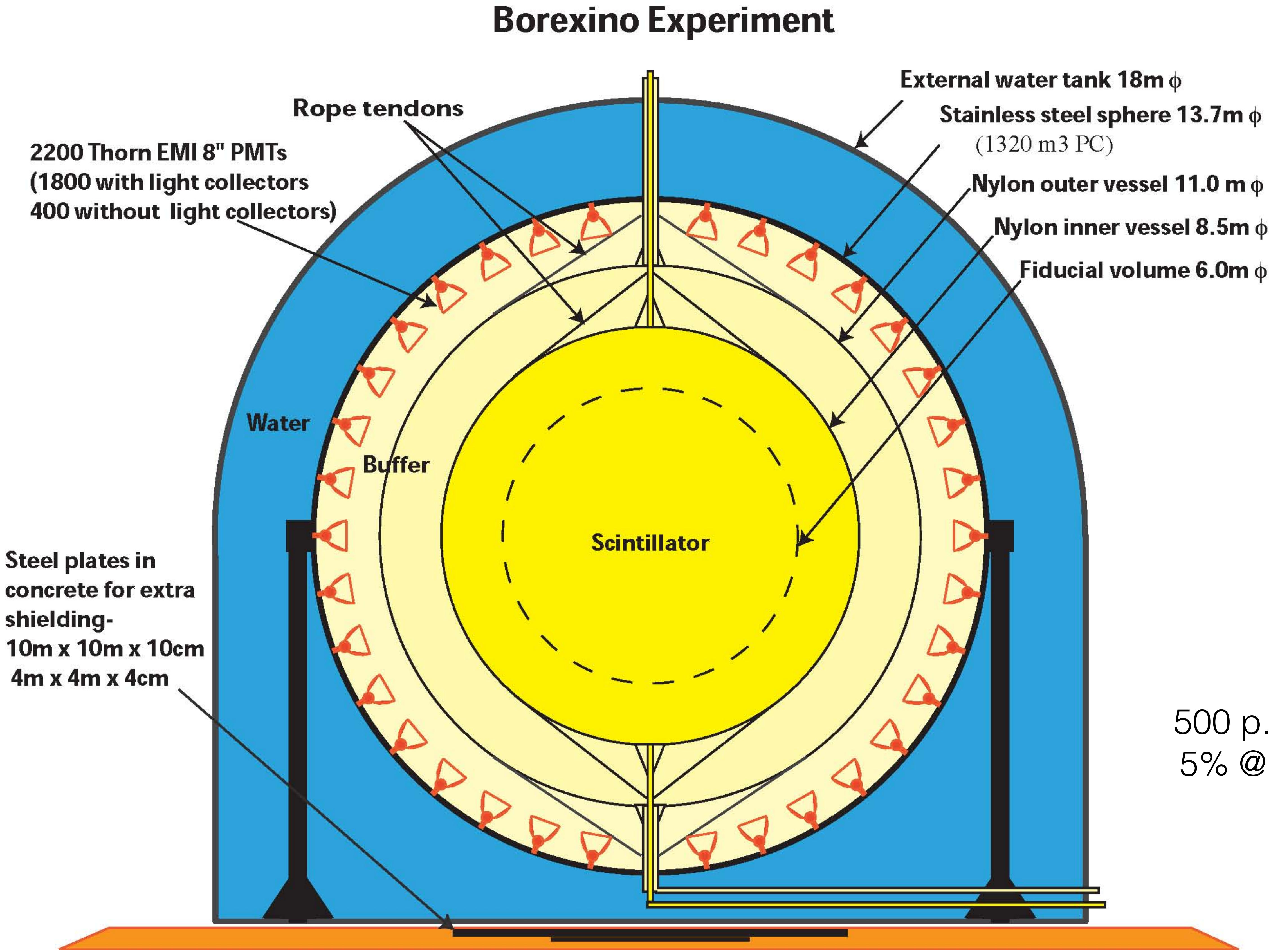
- Borexino is a **liquid scintillator detector**. Target mass 300 ton. Active mass **~70 ton** in this analysis.
  - Charged particles deposit energy and scintillation photons are produced.
  - Measure particle energy by Counting number of photons using PMTs.



- Solar neutrinos are detected via **Elastic Scattering.**
  - only the recoil electron are detected.

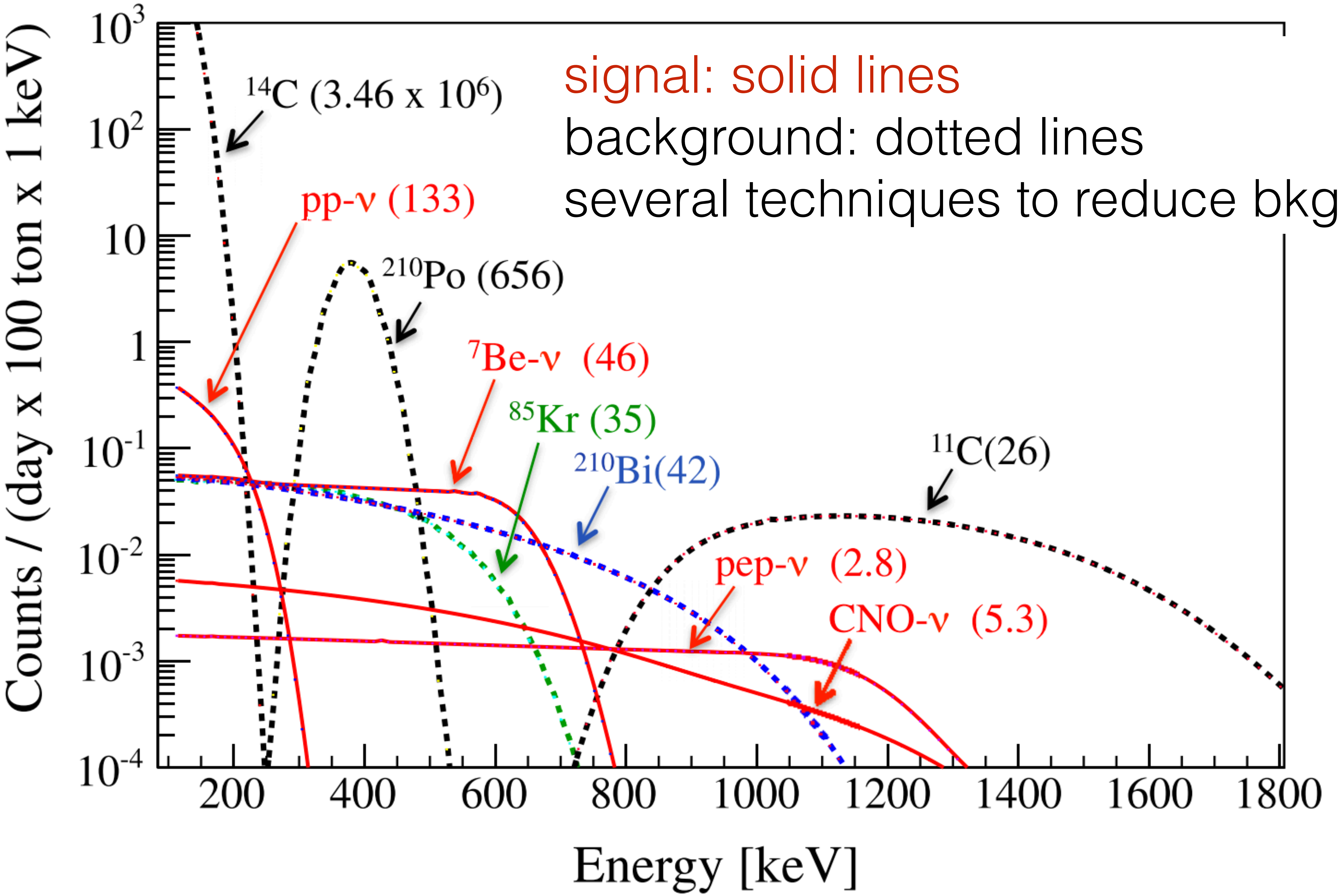


Borexino detector



500 p.e./MeV
5% @ 1 MeV

Expected Signal and backgrounds



signal: solid lines

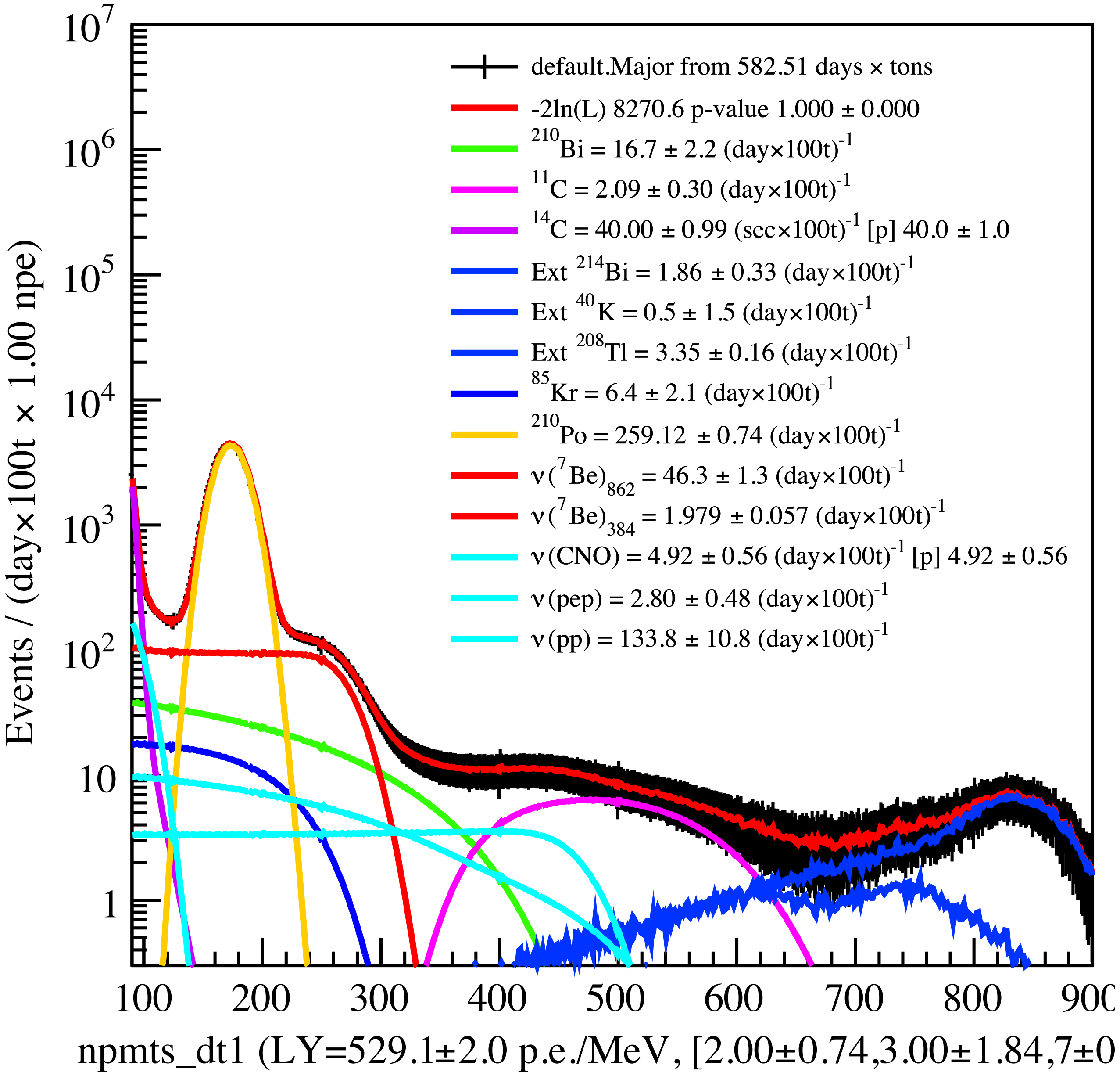
background: dotted lines

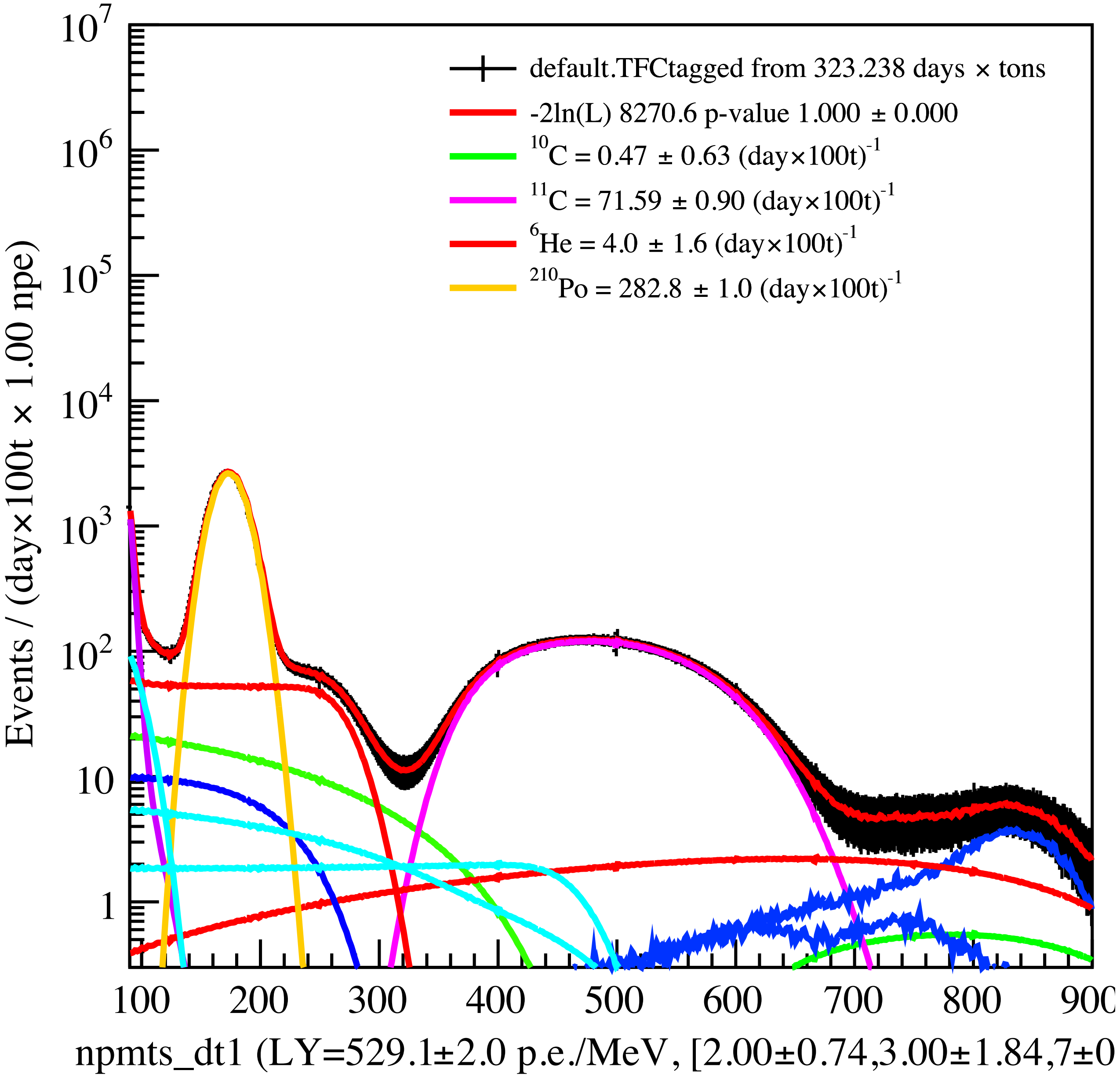
several techniques to reduce bkg.

G. Bellini et al., “**Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy**,” *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, vol. 89, no. 11, pp. 1–68, 2014.

Borexino basics: Spectrum fit

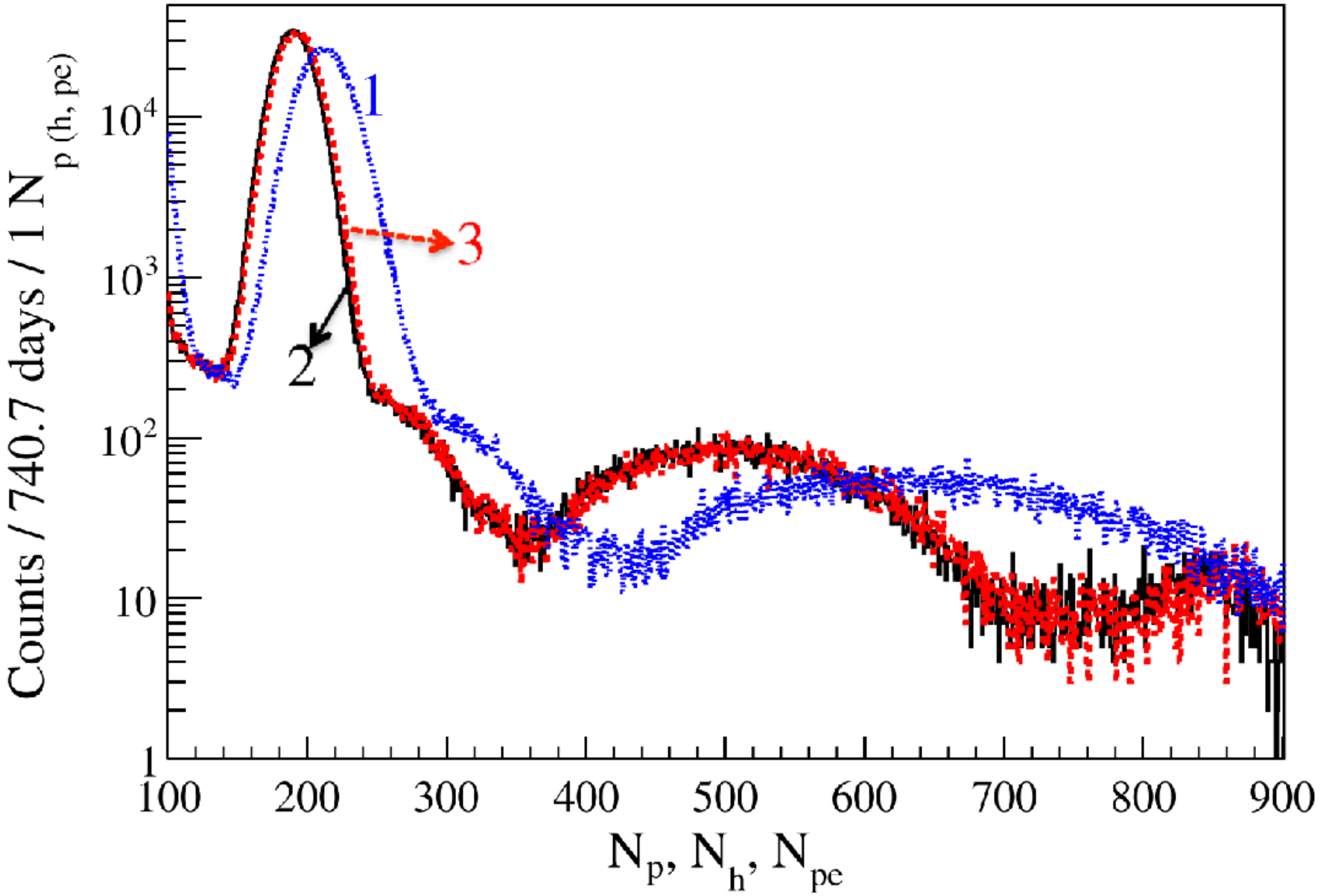
- Obtain interaction rates by “fitting”




Asimov dataset

Borexino basics: 3 energy estimators

- **N_p**, or **npmt_dt1**: number of fired PMTs;
- **N_h**, or **nhit**: number of collected hits;
- **N_{pe}**, or **charge**: sum of charge of all hits



G. Bellini et al., "**Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy**," *Phys. Rev. D - Part. Fields, Gravit. Cosmol.*, vol. 89, no. 11, pp. 1–68, 2014.

Borexino basics: 2 fit methods

- **Monte Carlo** fit: simulate detector response (GEANT4).
- **Analytical** fit: describe detector response analytically.

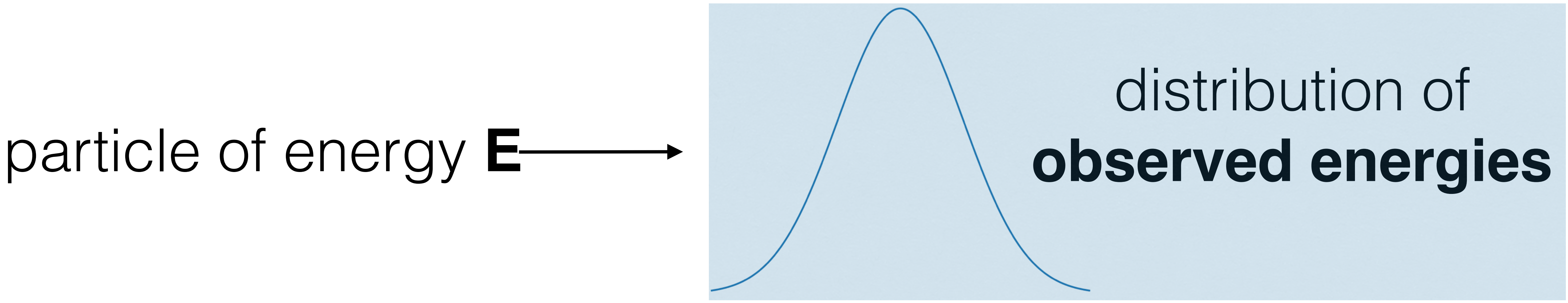
Monte Carlo

- **Tuned to calibration**
- **^{14}C: real time "calibration"**
- Precise geometrical effect.
- Fitting time short.

Analytical fit

- **Extract detector response information from data.** (light yield, energy resolution model)
- **Some parameters fixed to MC (calibration)**
- Fitting time long (~hours)

[ch4] Development of Analytical response

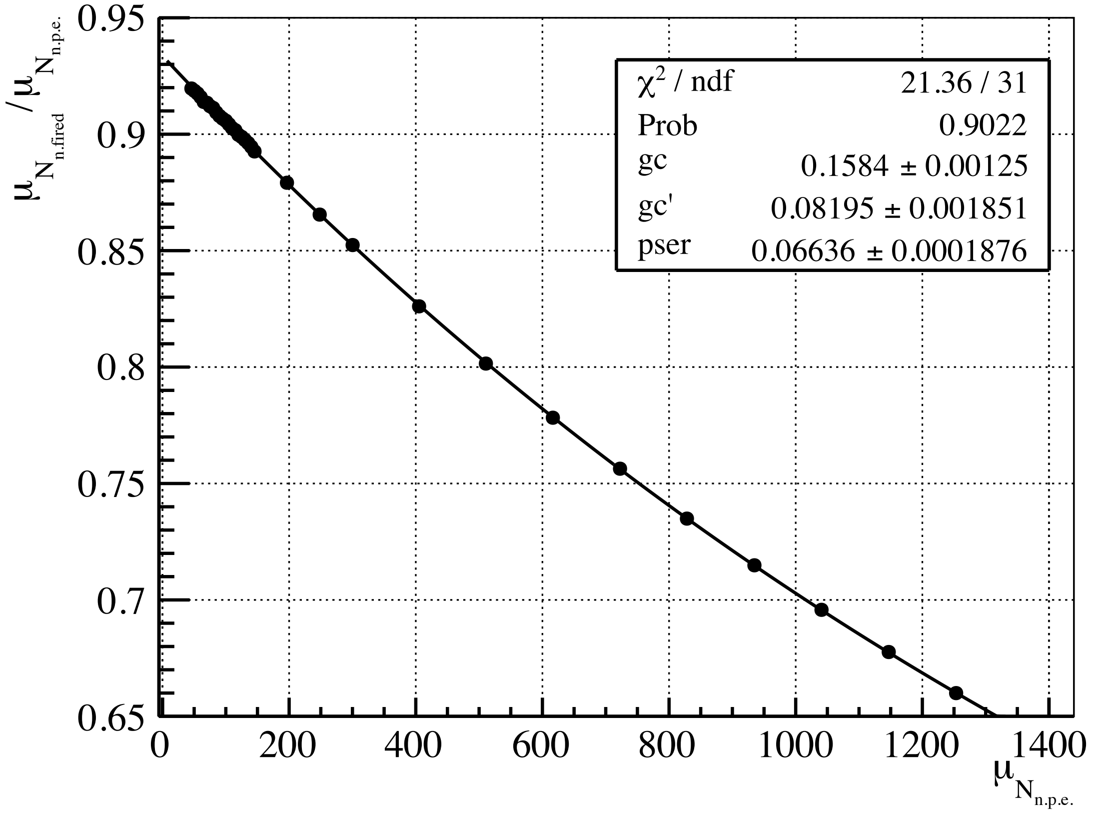


particle of energy **E** →

distribution of
observed energies

- **Response function**: the distribution of observed energies for a particle of energy **E**
- How we determine the distribution? **momentum of the distribution**.
  - Model energy -> **average** (energy scale + non-linearity model)
  - Model energy -> **variance** (energy resolution model)
  - Model energy -> **skewness**
  - Calculate parameters using average, variance, skewness…

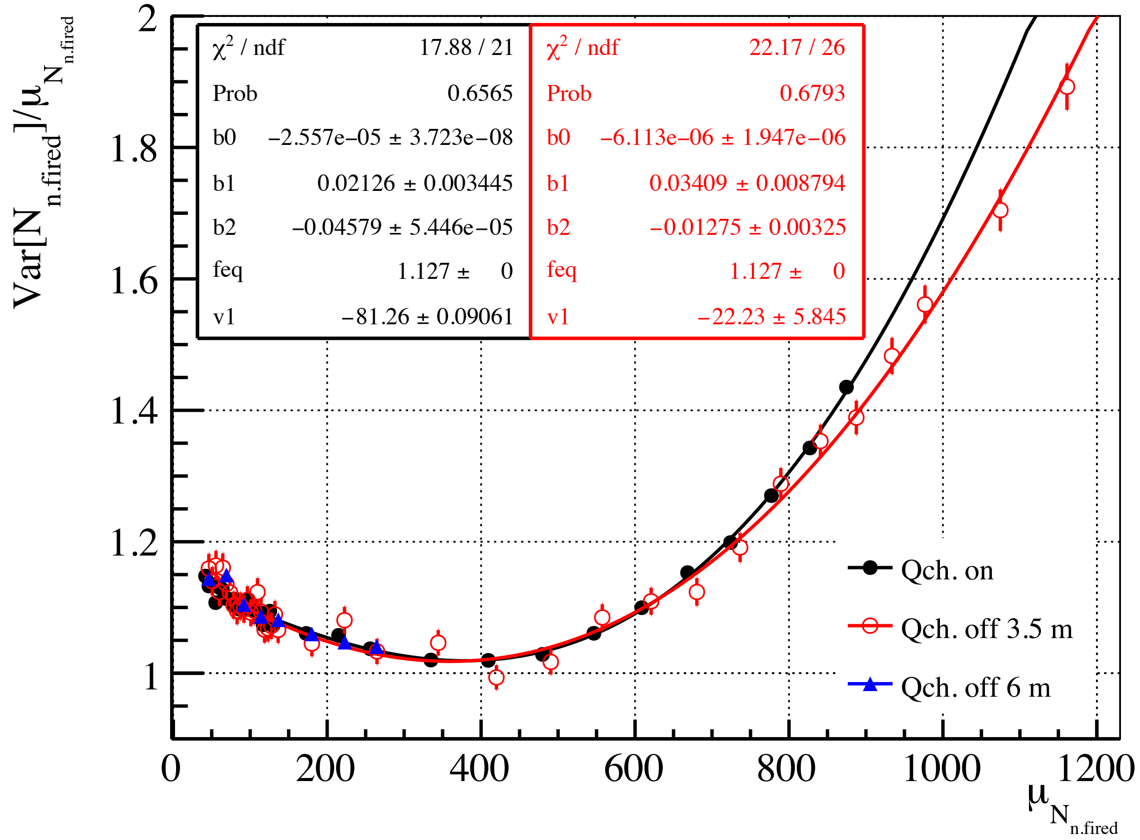
[ch4] E -> average / variance



Average (of distribution of observed energies)

$$\mu_{\text{p.e.}} = \varepsilon(\mathbf{r}) \cdot Y_{\text{p.e.}} \cdot \left(f_{\text{qch.}}(E) + \mu_{L_{\text{Cher.}}}(E) \cdot \text{fCher}\right)$$

$$\frac{\mu^{\text{FV}}_{\text{n.fired}}}{N_{\text{PMT}}} = \left[1 - (1 + p_{\text{ser}} \cdot r) \cdot e^{-r}\right] \cdot \left(1 - g_{\text{LC}} \cdot r + g'_{\text{LC}} \cdot r^2\right)$$

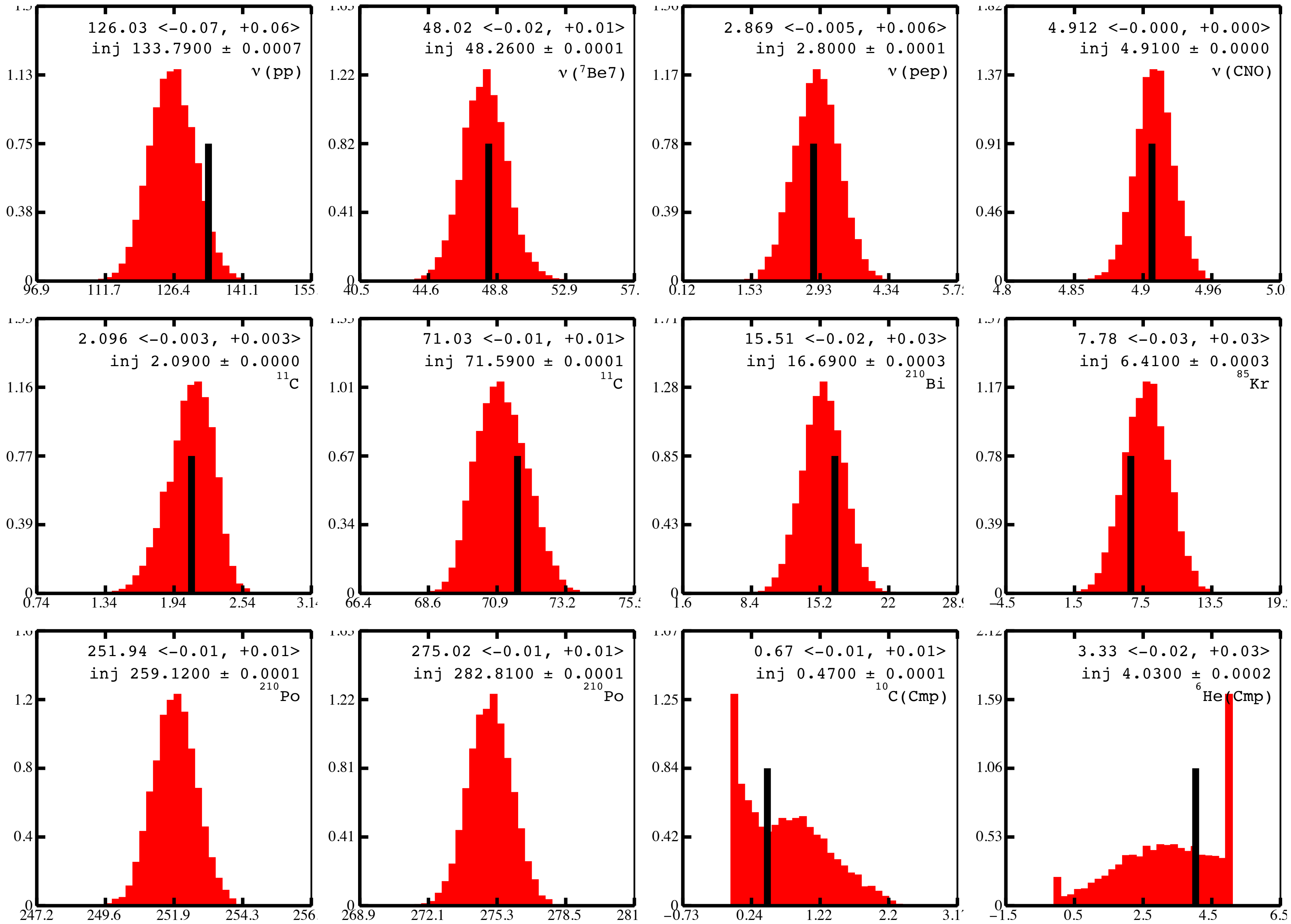


Variance (of distribution of observed energies)

$$\begin{aligned}
\text{Var}(N^{\text{FV}}_{\text{n.fired}}) = {} & f^{t}_{\text{eq.}} \cdot \mu^{\text{FV}}_{\text{n.fired}} \cdot [1 - r_v \cdot (1 + v_1)] \\
& + \beta_0 \cdot \left(\mu^{\text{FV}}_{\text{n.fired}}\right)^3 \cdot \left(f^{t}_{\text{eq.}}\right)^{-1} \\
& + \beta_1 \cdot \mu^{\text{FV}}_{\text{n.fired}} \cdot f^{t}_{\text{eq.}} \\
& + \beta_2 \cdot (N_{\text{n.live}} \cdot (1 - r_v) \cdot \ln(1 - r_v))^2
\end{aligned}$$

[ch4] Validation: npmt (# of fired PMTs)

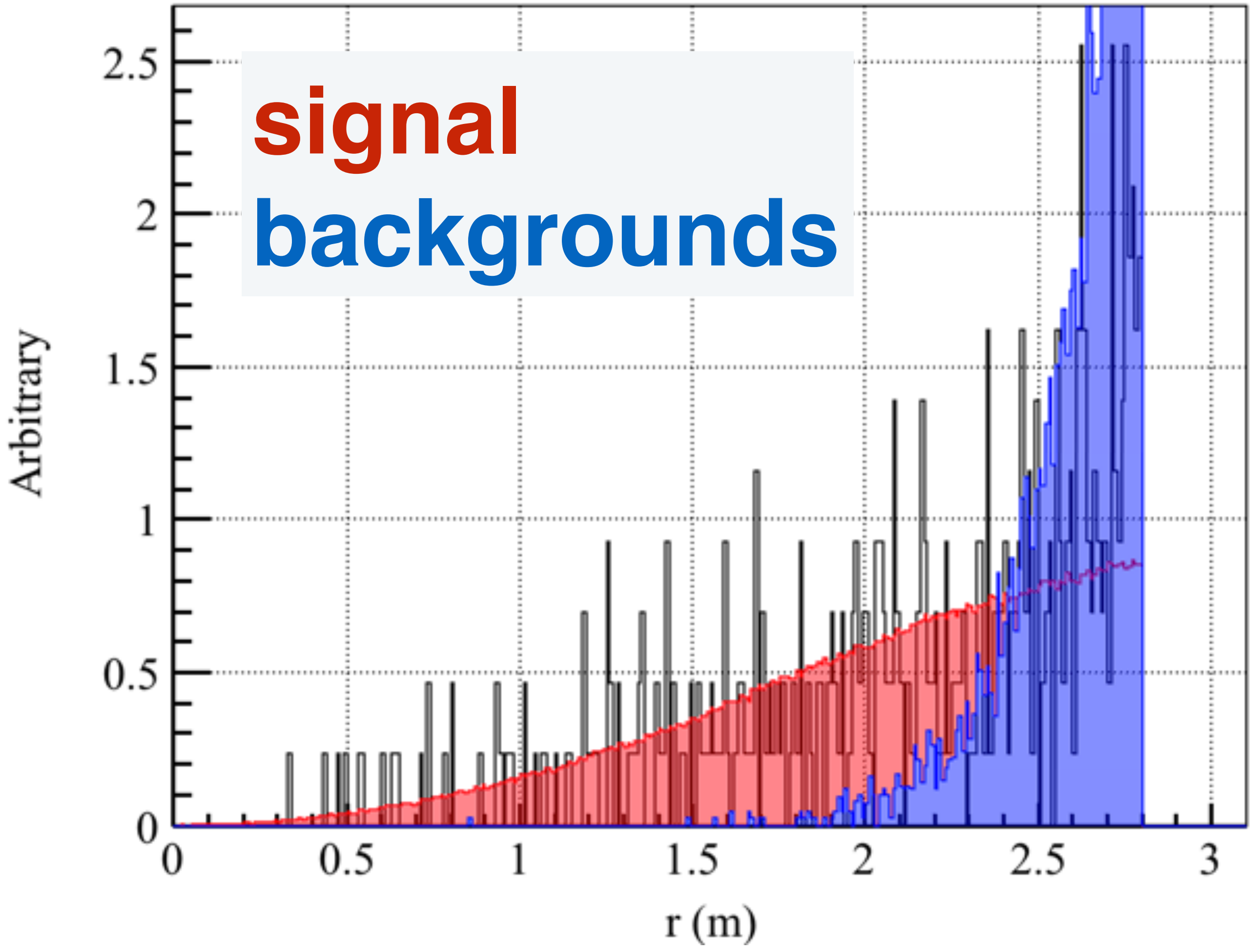
- Random sampling spectra from MC based p.d.f.'s
- Fit with analytical functions and compare fit results with inj.



Borexino basics: multivariate fit

- Use not only energy, but also position / pulse shape

$$\mathcal{L}^{\mathrm{MV}} = \mathcal{L}^{\mathrm{TFC\ vetoed}} \times \mathcal{L}^{\mathrm{TFC\ tagged}} \times \boxed{\prod_i \mathcal{L}_i^{\mathrm{radial}}} \times \prod_j \mathcal{L}_j^{\mathrm{pulse\text{-}shape}}$$



Distribution of “distance to detector center (r)” can be used to discriminate uniform events (neutrinos and bulk backgrounds) and γs from outside.

GPU fitter: a breakthrough

- 2016 Feb. Ilia: I added MINOS option so we can get precise error but it takes 8 hours.. me: hmm??
- 2017 New Year's Eve, GooStats v0.001
- 2017 Feb. 03 bx-GooStats-charge
- 2017 Mar. 19 bx-GooStats-MC-MV
- 2017 Mar. 23 bx-GooStats-npmt
- 2017 April My colleagues start to produce physics result with bx-GooStats

上午2:15

5 species, in 3 seconds 上午2:15

C11 and external need some more coding 上午2:15

super fast GPU fitting😁 上午2:15

👍👍👍 上午9:37

Happy new year 🍾🍾🍾 上午9:37

[ch3] GPU and Ana Multi-Variate

- 19 years -> 3 days for completing the analysis.

Computation Challenge for Borexino spectral analysis

100, 000 Multi-variate fits needed

CPU Sequential

> 19 year x 100 CPU

>1 week CPU / fit

~ 2.8 day x 100 GPU

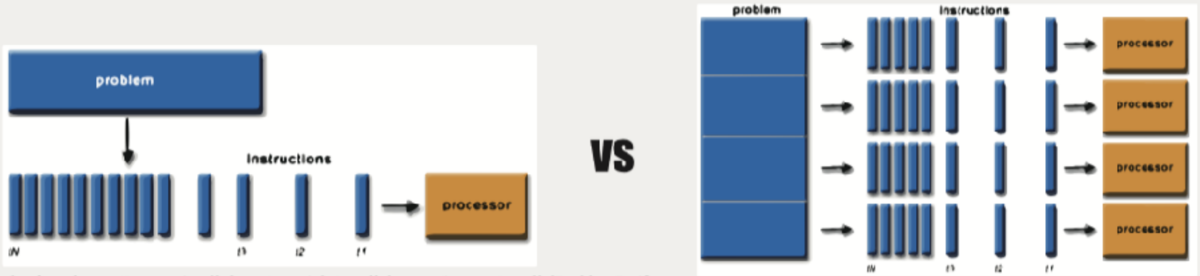
4 mins GPU / fit

GPU Parallel

Parallel computing

This project is based on C++11, ROOT, cuda and GooFit

Parallel computing: divide into small tasks and solved simultaneously

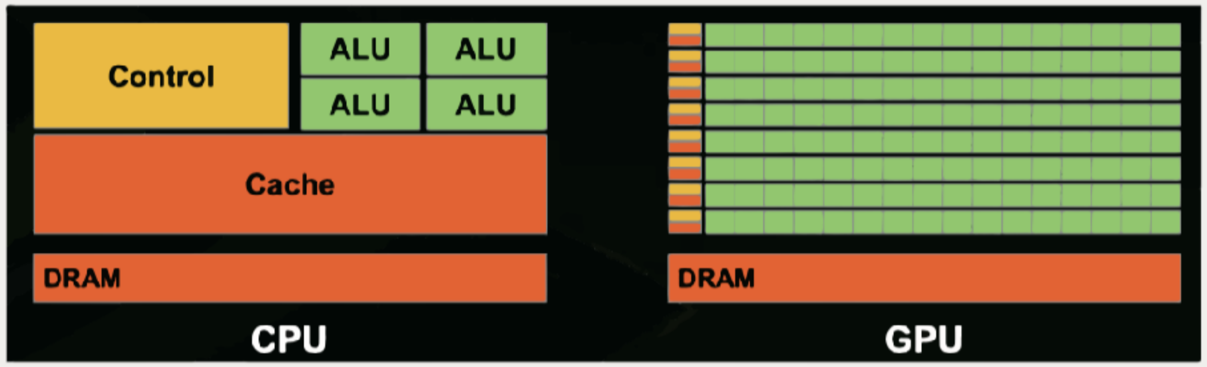


plot from https://computing.llnl.gov/tutorials/parallel_comp/images/parallelProblem2.gif

Graphic Processing Unit: thousands of cores, data parallelization

CPU: large cache, instruction parallization

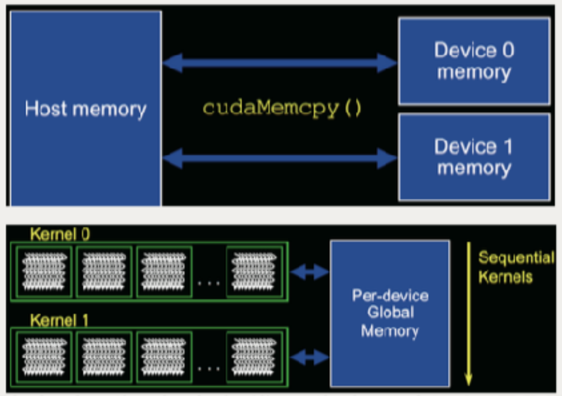
GPU: thousands of cores, data parallization



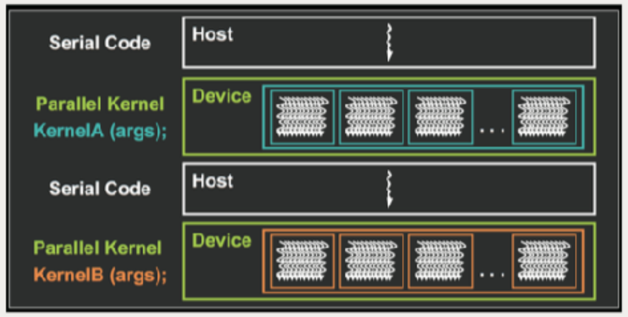
plot from https://www.ogf.org/OGF25/materials/1605/CUDA_Programming.pdf

Scheme of Graphic Processing Unit based parallization

Memory management



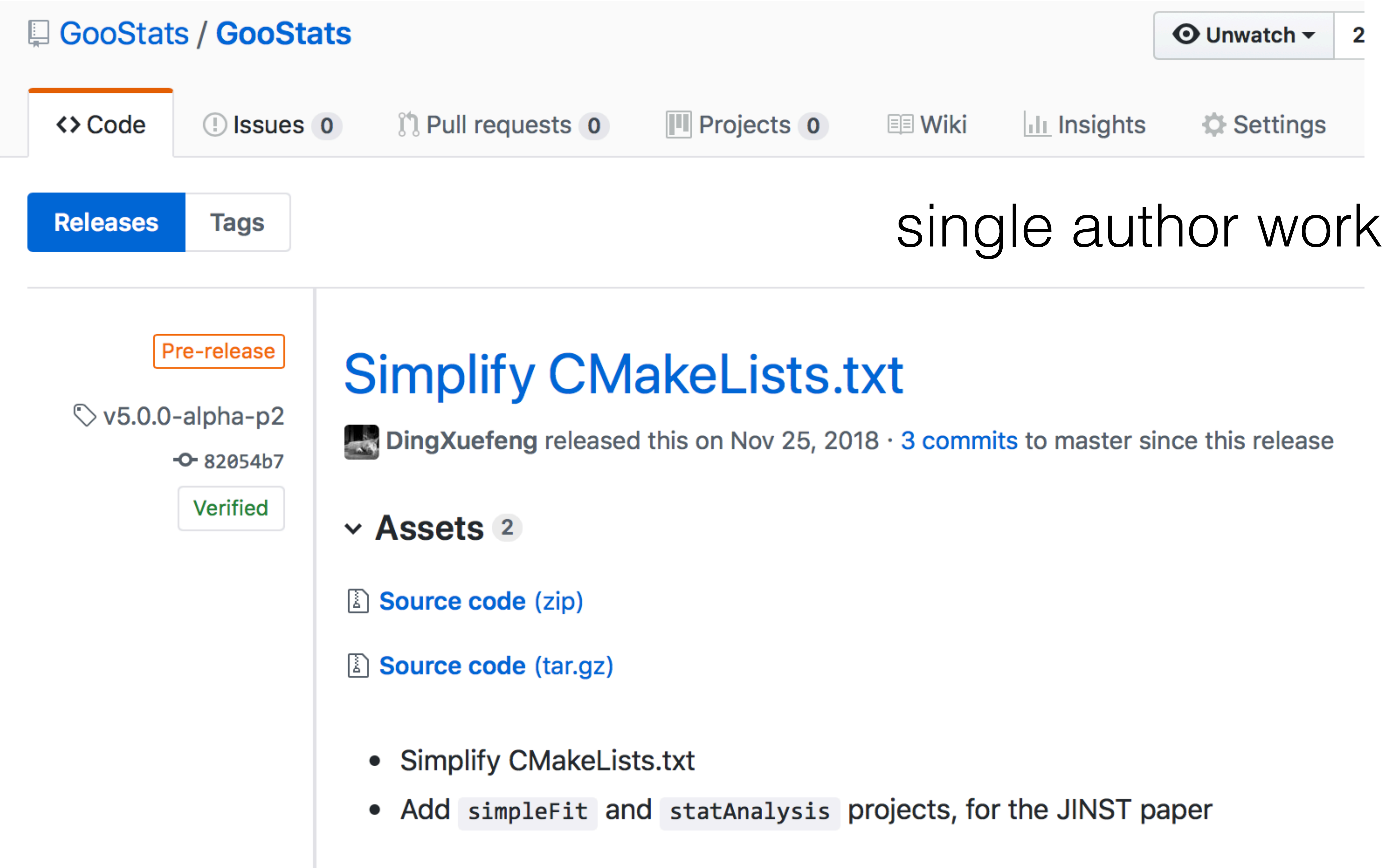
Program flow



plot from http://http.download.nvidia.com/developer/cuda/seminar/TDCI_CUDA.pdf

[ch3] GooStats: open source software

https://github.com/GooStats/GooStats.git



Simplify CMakeLists.txt

DingXuefeng released this on Nov 25, 2018 · 3 commits to master since this release

Assets 2

Source code (zip)

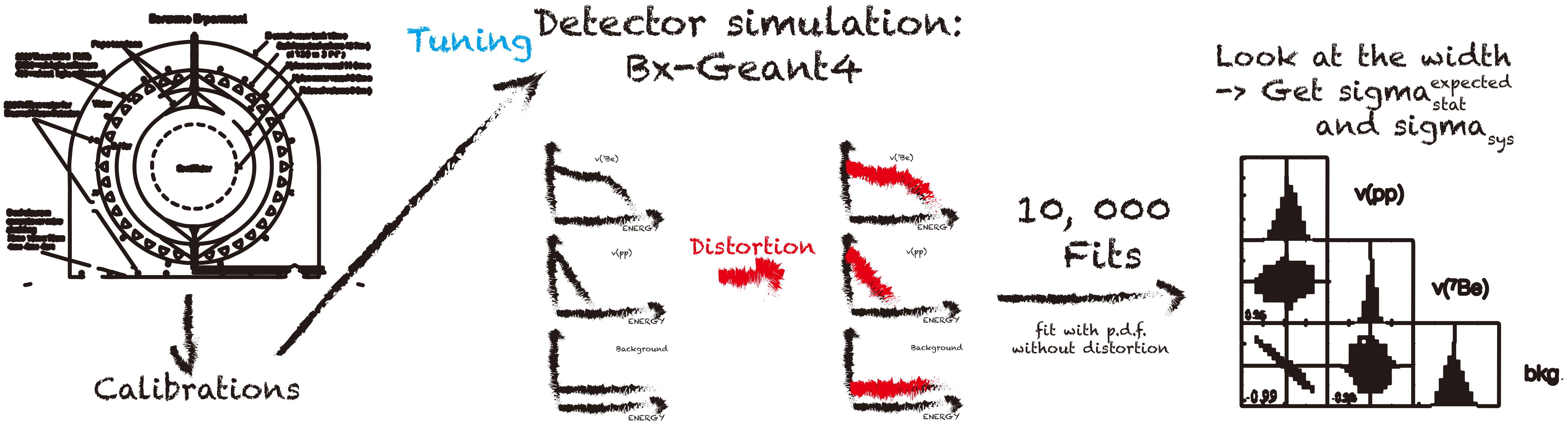
Source code (tar.gz)

- Simplify CMakeLists.txt
- Add `simpleFit` and `statAnalysis` projects, for the JINST paper

single author work

X. F. Ding, "**GooStats: A GPU-based framework for multi-variate analysis in particle physics**," *J. Instrum.*, vol. 13, no. 12, pp. P12018–P12018, Dec. 2018.

[ch5] Evaluation of systematic uncertainties



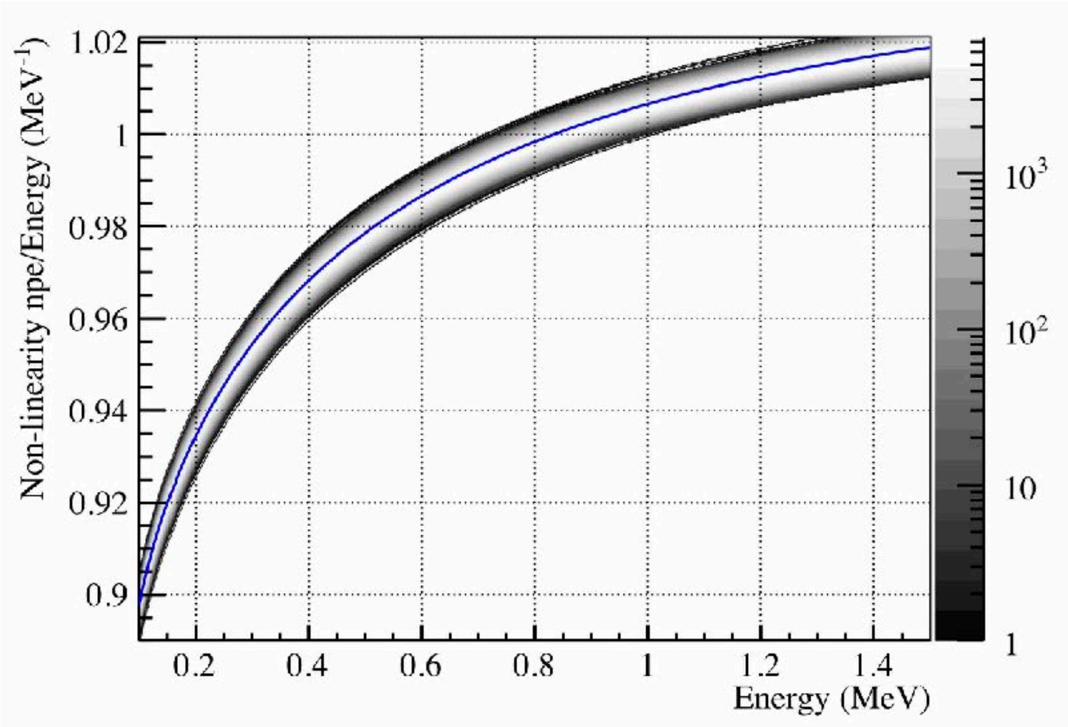
- pseudo-experiment spectra without distortion —> **statistical sensitivity**

- pseudo-experiment spectra with distortion —> **statistical** + **systematic uncertainty**

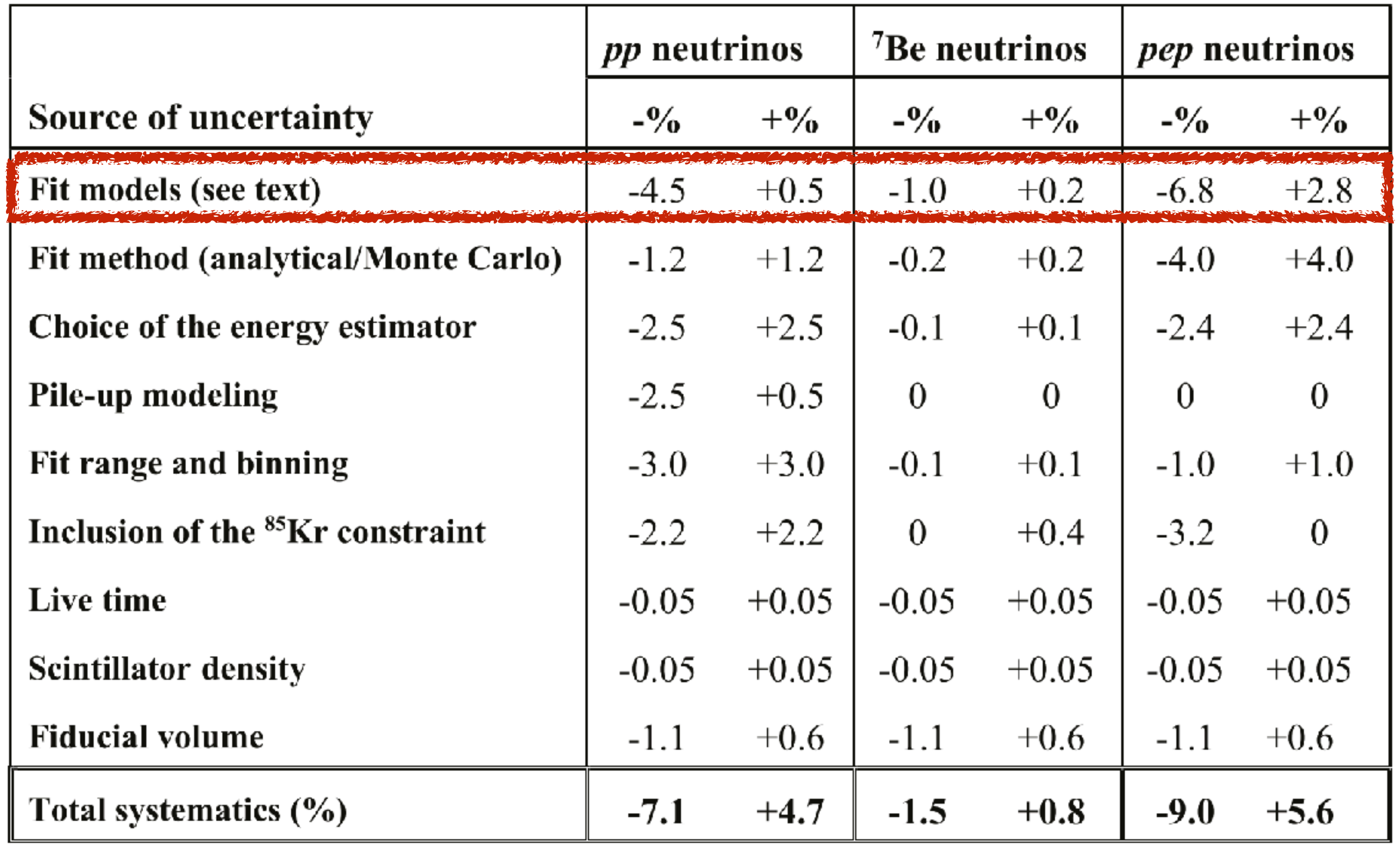
[ch5] Evaluation of systematic uncertainties

- Given an allowed range of distortion, a systematic uncertainty can be given.

Allowed range of non-linearity



M. Agostini et al., "**Comprehensive measurement of pp-chain solar neutrinos**," *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.



	***pp* neutrinos**		**^{7}Be neutrinos**		***pep* neutrinos**	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/Monte Carlo)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
Pile-up modeling	-2.5	+0.5	0	0	0	0
Fit range and binning	-3.0	+3.0	-0.1	+0.1	-1.0	+1.0
Inclusion of the ^{85}Kr constraint	-2.2	+2.2	0	+0.4	-3.2	0
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Fiducial volume	-1.1	+0.6	-1.1	+0.6	-1.1	+0.6
Total systematics (%)	**-7.1**	**+4.7**	**-1.5**	**+0.8**	**-9.0**	**+5.6**

Relevant sources of systematic uncertainties and their contributions to the measured neutrino interaction rates for the LER analysis.

[ch6] Measurement results

2007 May -
2010 May
Phase-I

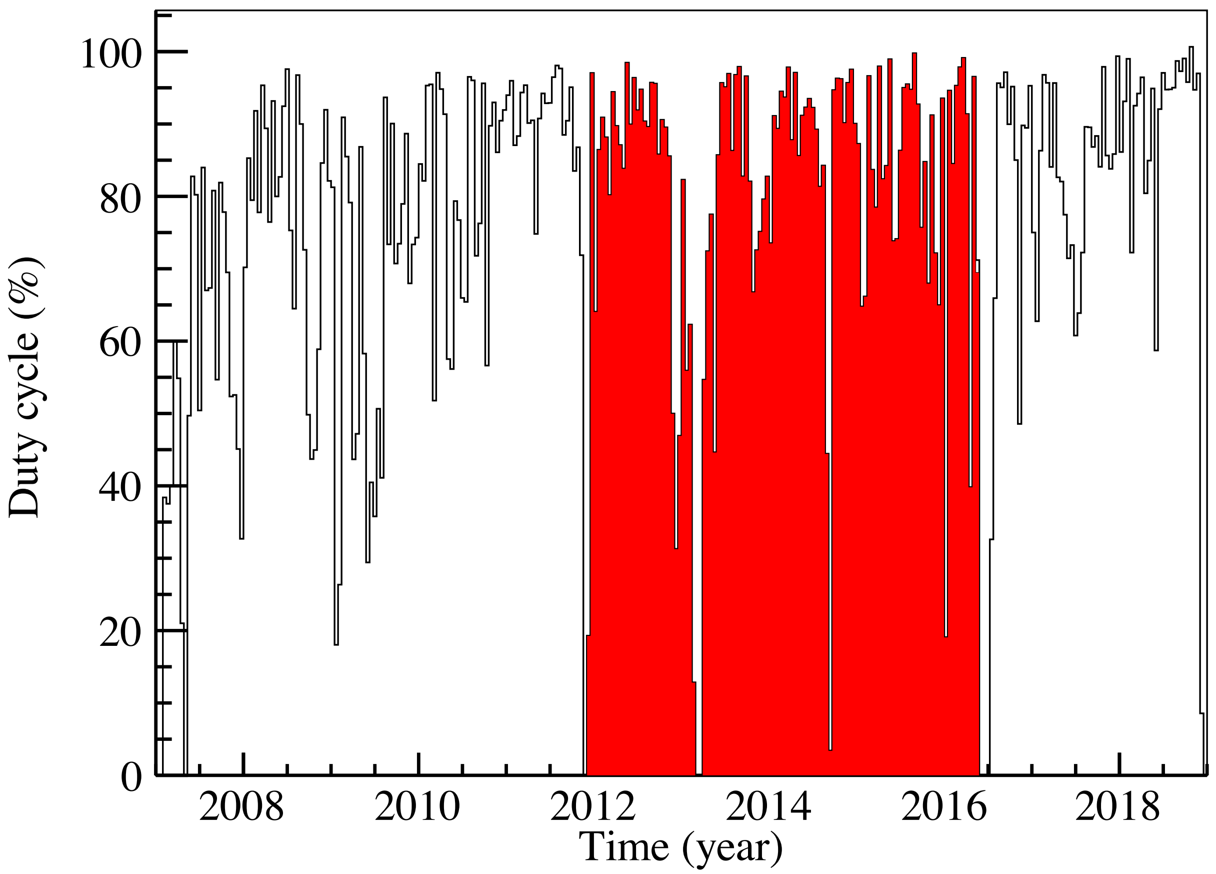
2010-2011
Purification +
Calibration

2011 Dec - 2016 May
Phase-II

2016 June - now
Phase-III

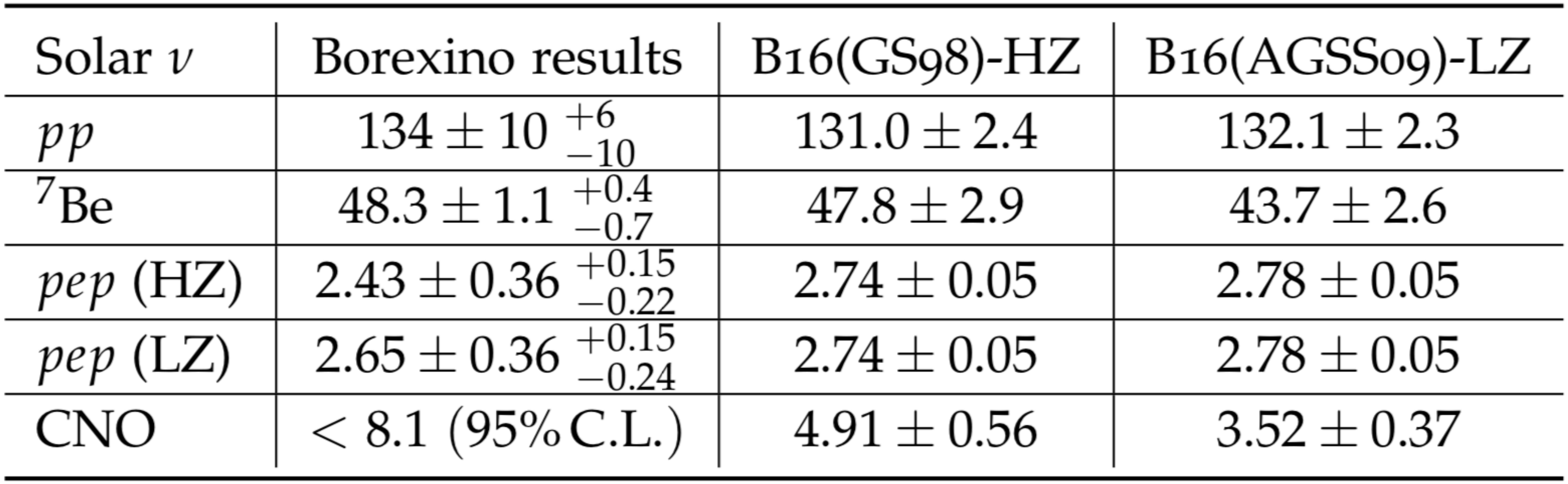
- Based on data collected in **Phase-II**
- Exposure:
  - 1291.51 days × 71.3 t

Duty cycle



[ch6] Measurement results

- pp, pep, ^{7}Be solar neutrinos: CNO constrained to HZ/LZ
- CNO limit: pp/pep ratio constrained

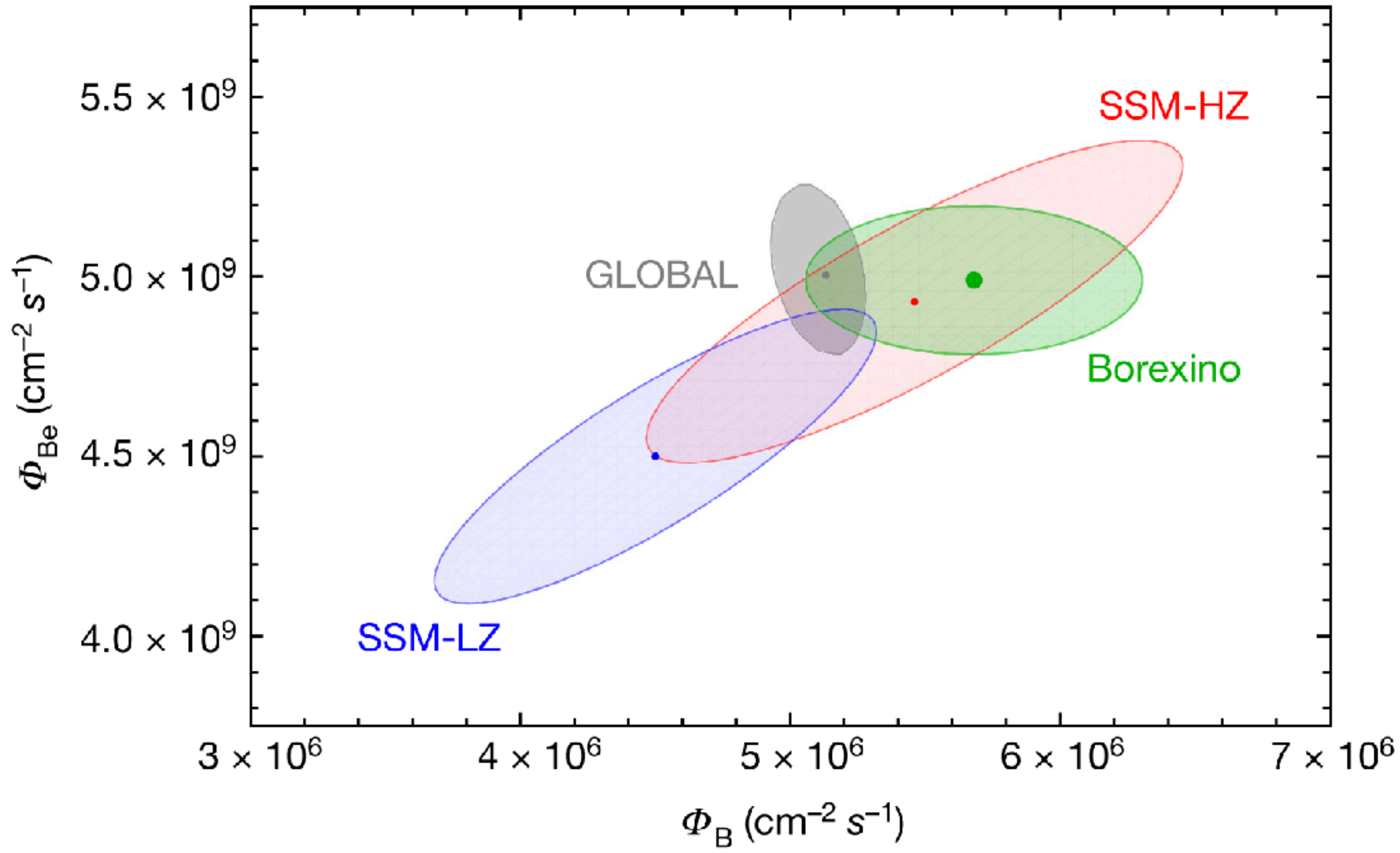


Solar ν	Borexino results	B16(GS98)-HZ	B16(AGSS09)-LZ
pp	$134 \pm 10\ ^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.3
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05
CNO	< 8.1 (95% C.L.)	4.91 ± 0.56	3.52 ± 0.37

M. Agostini et al., "**Comprehensive measurement of pp-chain solar neutrinos**," *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.

[ch6] Measurement results

- Assuming P_{ee}: measure solar neutrino flux

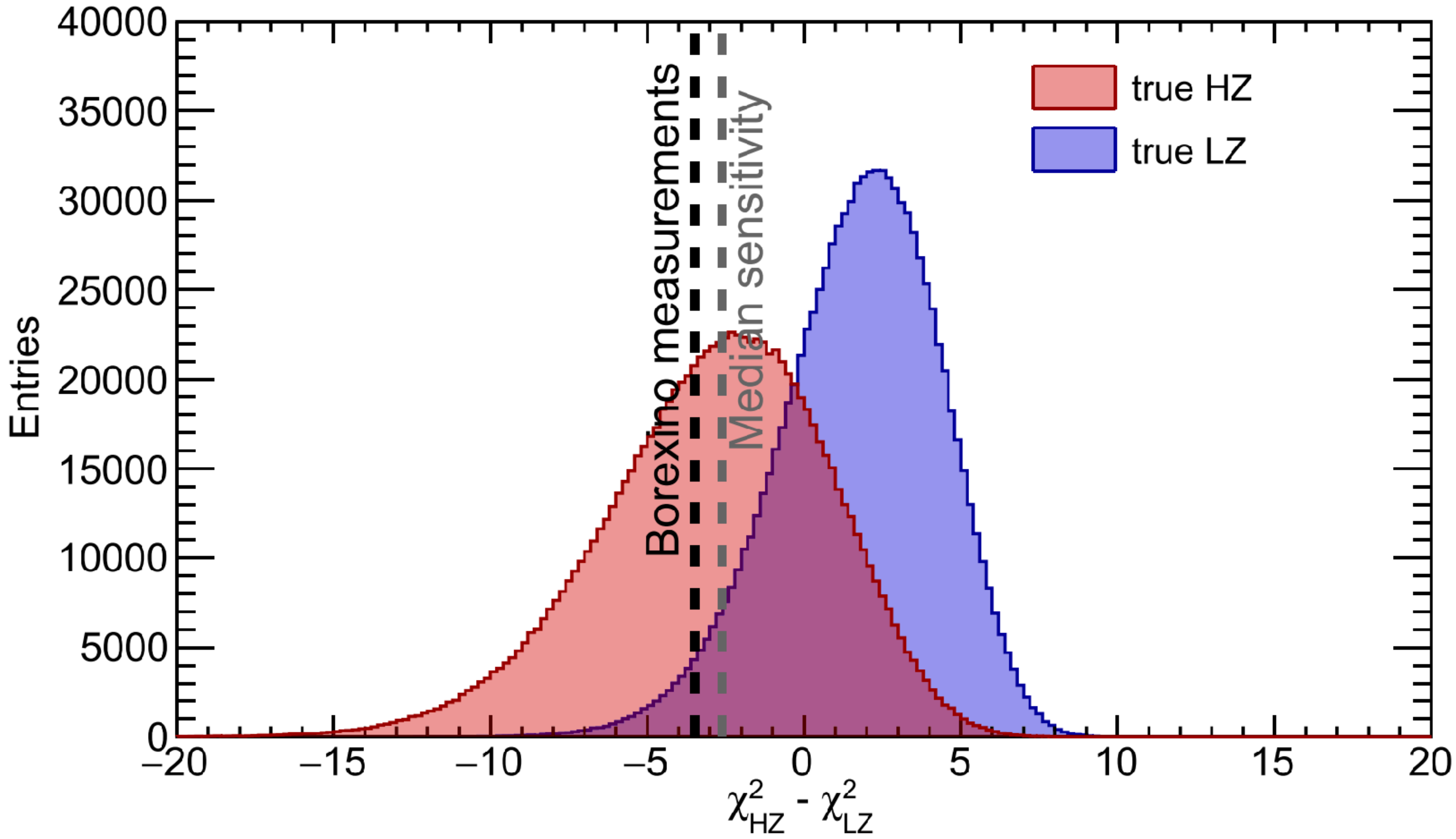


Solar ν	Borexino results	B16(GS98)-HZ	B16(AGSS09)-LZ
pp	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	$5.98\,(1 \pm 0.006) \times 10^{10}$	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	$4.93\,(1 \pm 0.06) \times 10^{9}$	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	$< 7.9 \times 10^{8}$ (95% C.L.)	$4.88\,(1 \pm 0.11) \times 10^{8}$	$3.51\,(1 \pm 0.10) \times 10^{8}$
^{8}B	$(5.68^{+0.39}_{-0.41}\ ^{+0.03}_{-0.03}) \times 10^{6}$	$5.46\,(1 \pm 0.12) \times 10^{6}$	$4.50\,(1 \pm 0.12) \times 10^{6}$

M. Agostini et al., “**Comprehensive measurement of pp-chain solar neutrinos**,” *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.

[ch6] Hypothesis test

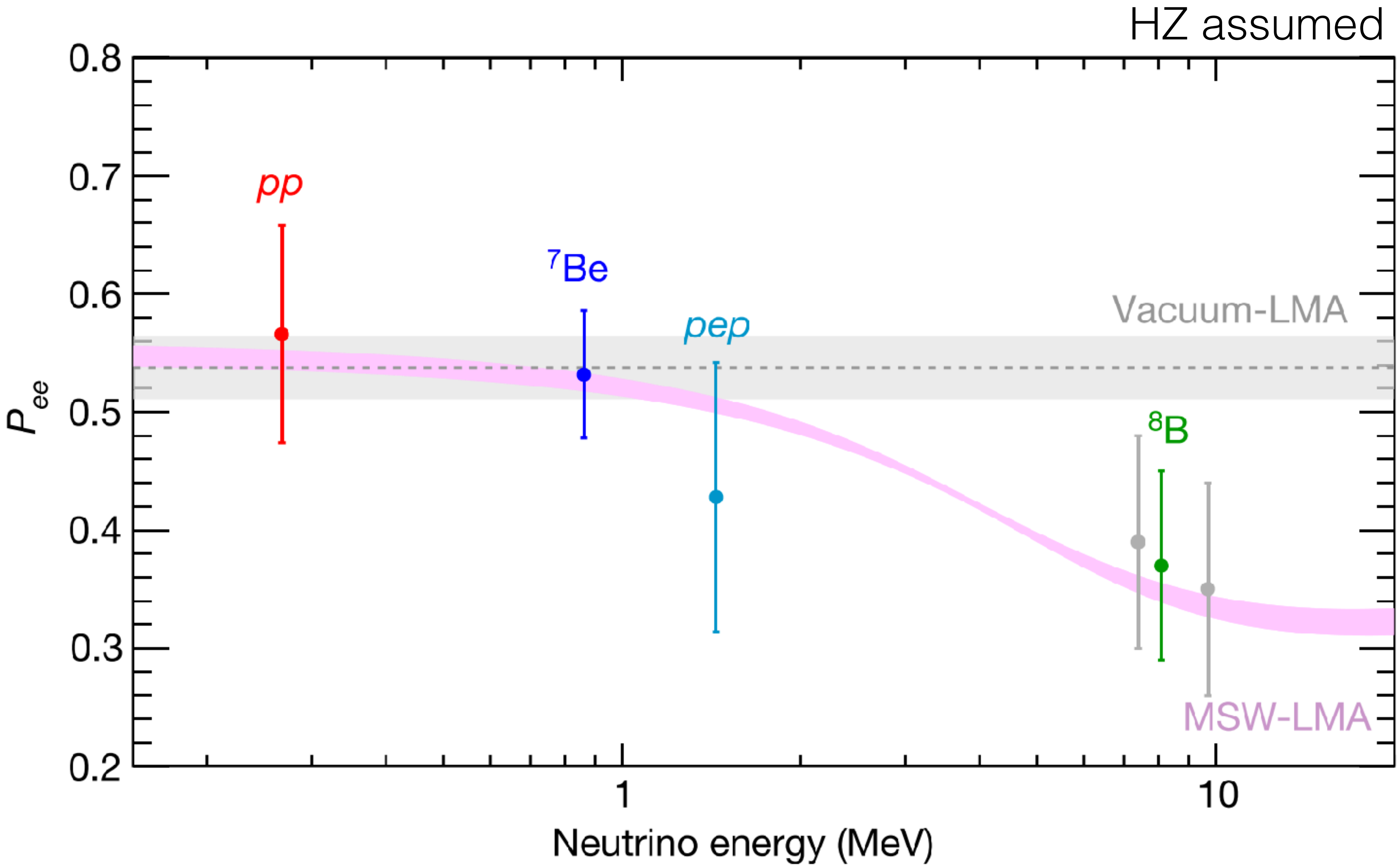
- Mild preference for LZ (96.6% CL, or 2.2 σ)



M. Agostini et al., “**Comprehensive measurement of pp-chain solar neutrinos**,” *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.

[ch6] Measurement results

- Assuming solar neutrino flux: measure P_{ee}
- Results match well with predictions using **KamLAND results**.



M. Agostini et al., “**Comprehensive measurement of pp-chain solar neutrinos**,” *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.

Summary of my contribution

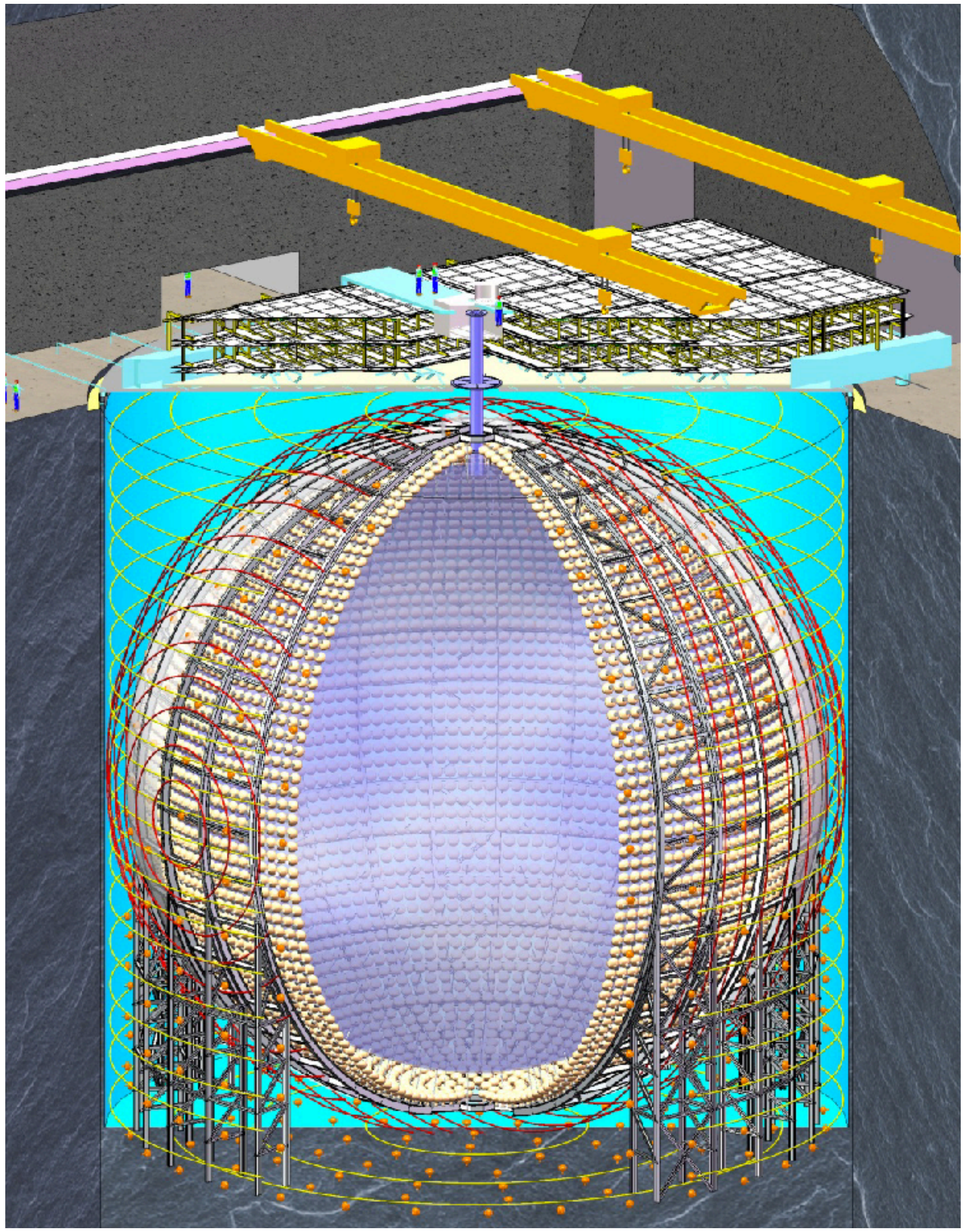
- New GPU software: breakthrough for Borexino analysis
- New analysis procedure: analytical multivariate analysis
- Measurement using "**charge**"
- Full evaluation of the systematic uncertainties through a comprehensive toyMC approach

Potential of JUNO

Chapter 10, 11

JUNO detectors

- **Center Detector**
  - Acrylic sphere containing **L**iquid **S**cintillator(LS)
  - PMT in water (18k 20” + 25k 3”)
  - 20 kt LS + 78% photocathode coverage
- **Veto Detector (μ tagger)**
  - Water Cherenkov detector
  - Top tracker
  - For μ tagging and track reconstruction
- **Calibration System**
  - 4 complementary sub-system
  - Covering various particle type, full energy range and position

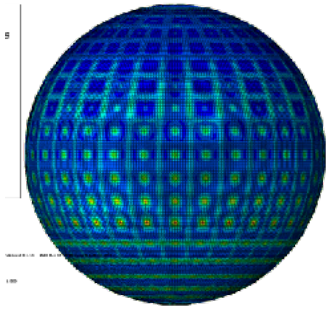


DocDB 1486

Milestone & schedule

2014:

- International collaboration established
- Start civil construction



2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production

2017:

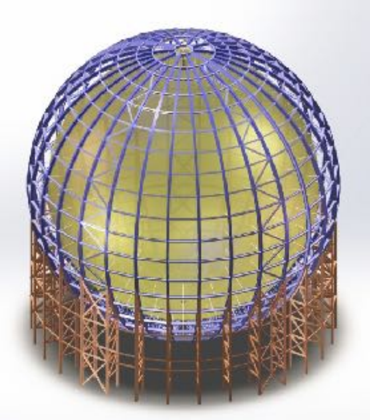
- Start PMT testing
- TT arrived

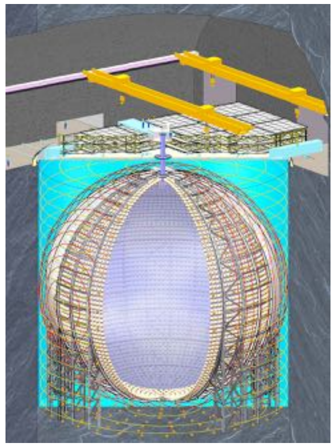
2018:

- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector constructing





2021:

- Detector ready for Data taking!

Medium-baseline reactor ν exp.

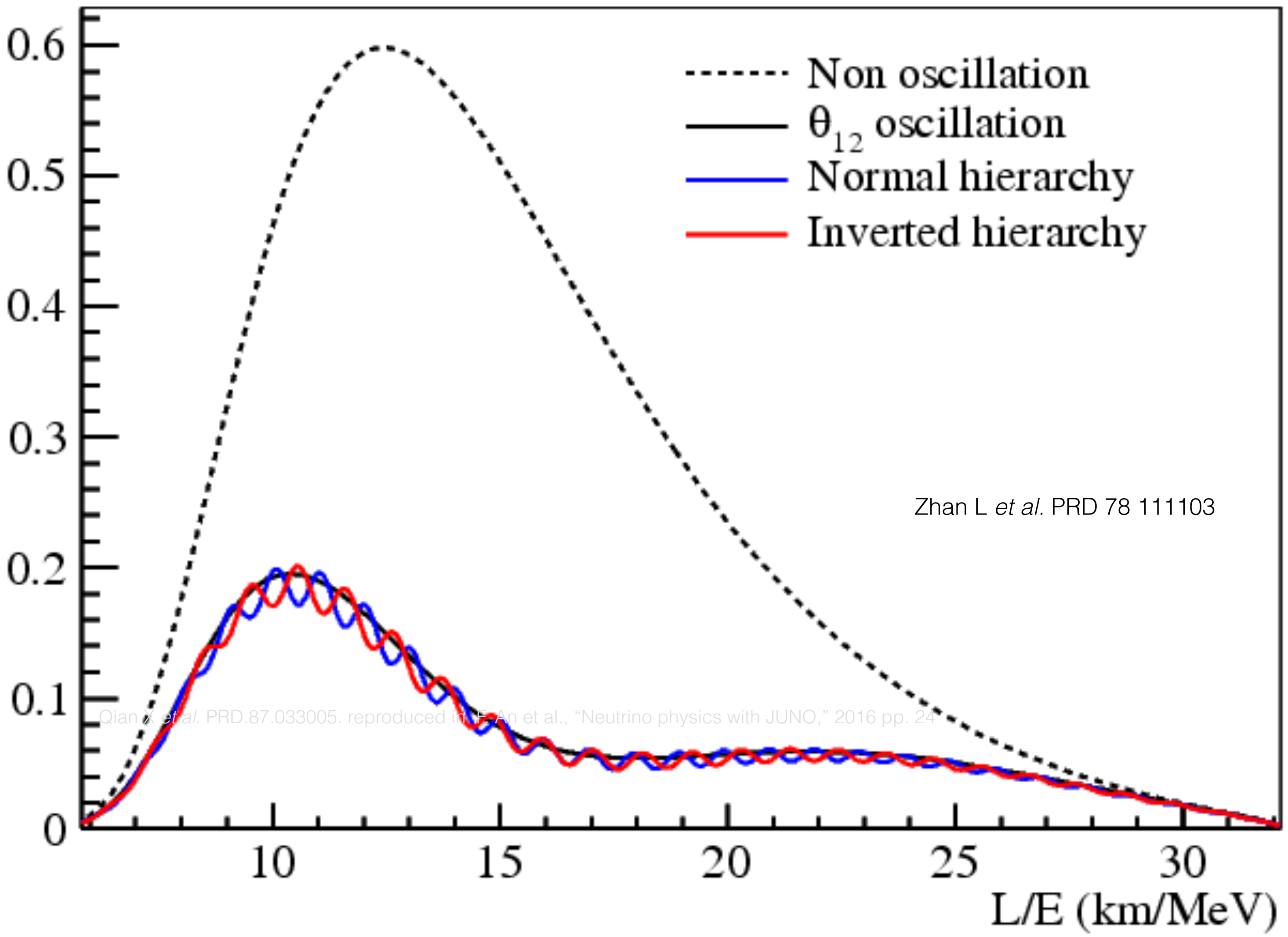
$$P_{ee}\left(\xi\right) = a_0\left(\xi\right) + a_1\left(\xi\right) \cdot {\color{blue} \sin^2 2\theta_{13}} \cdot \cos\left[1.27 \left(2\Delta m_{ee}^2 {\color{red}\pm \Delta m_\phi^2}\right) \cdot \xi\right]$$

S. T. Petcov and M. Piai, "**The LMA MSW solution of the solar neutrino problem, inverted neutrino mass hierarchy and reactor neutrino experiments**," *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.*, vol. 533, no. 1–2, pp. 94–106, 2002.

$$\xi = \frac{L\,(\mathrm{m})}{E\,(\mathrm{MeV})}$$

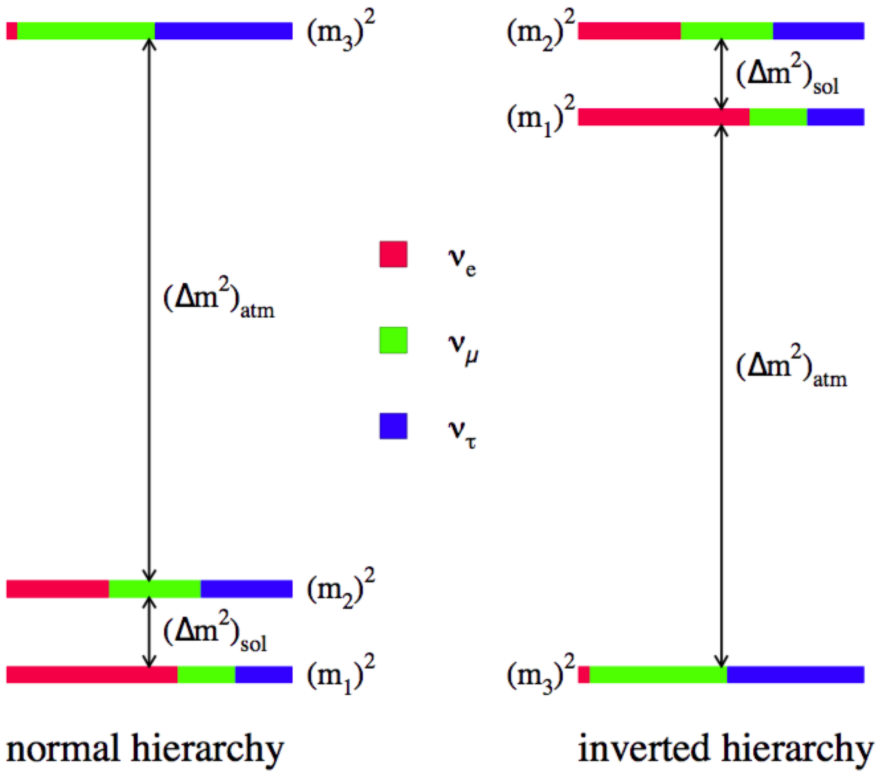
P_{ee}\left(\xi\right) = a_0\left(\xi\right) + a_1\left(\xi\right) \cdot {\color{blue} \sin^22\theta_{13}} \cdot \cos\left[1.27 \left(2\Delta m_{ee}^2 {\color{red}\pm \Delta m_\phi^2 }\right) \cdot \xi\right]

Relative shape difference of Anti-ν flux



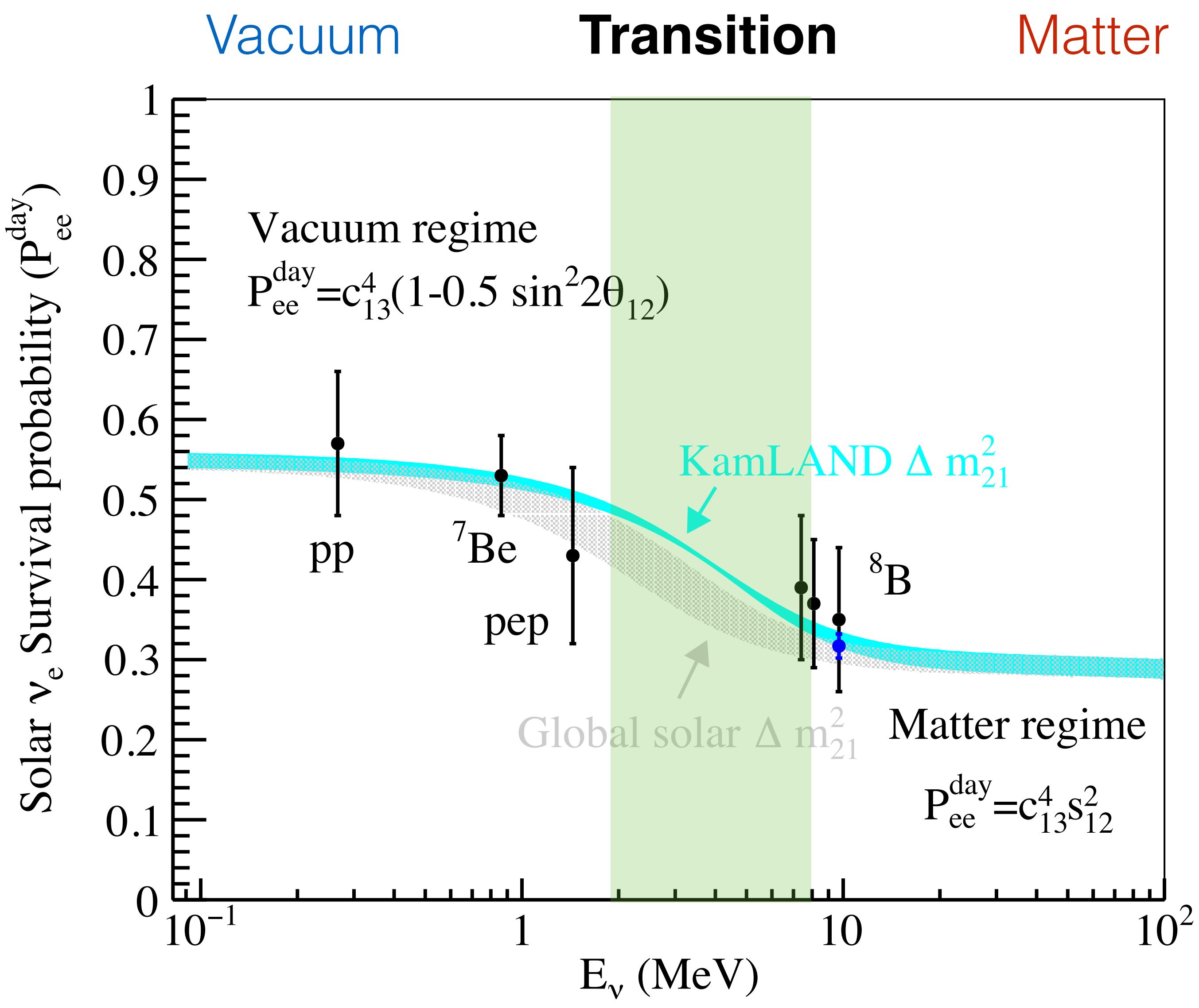
Zhan L *et al.* PRD 78 111103

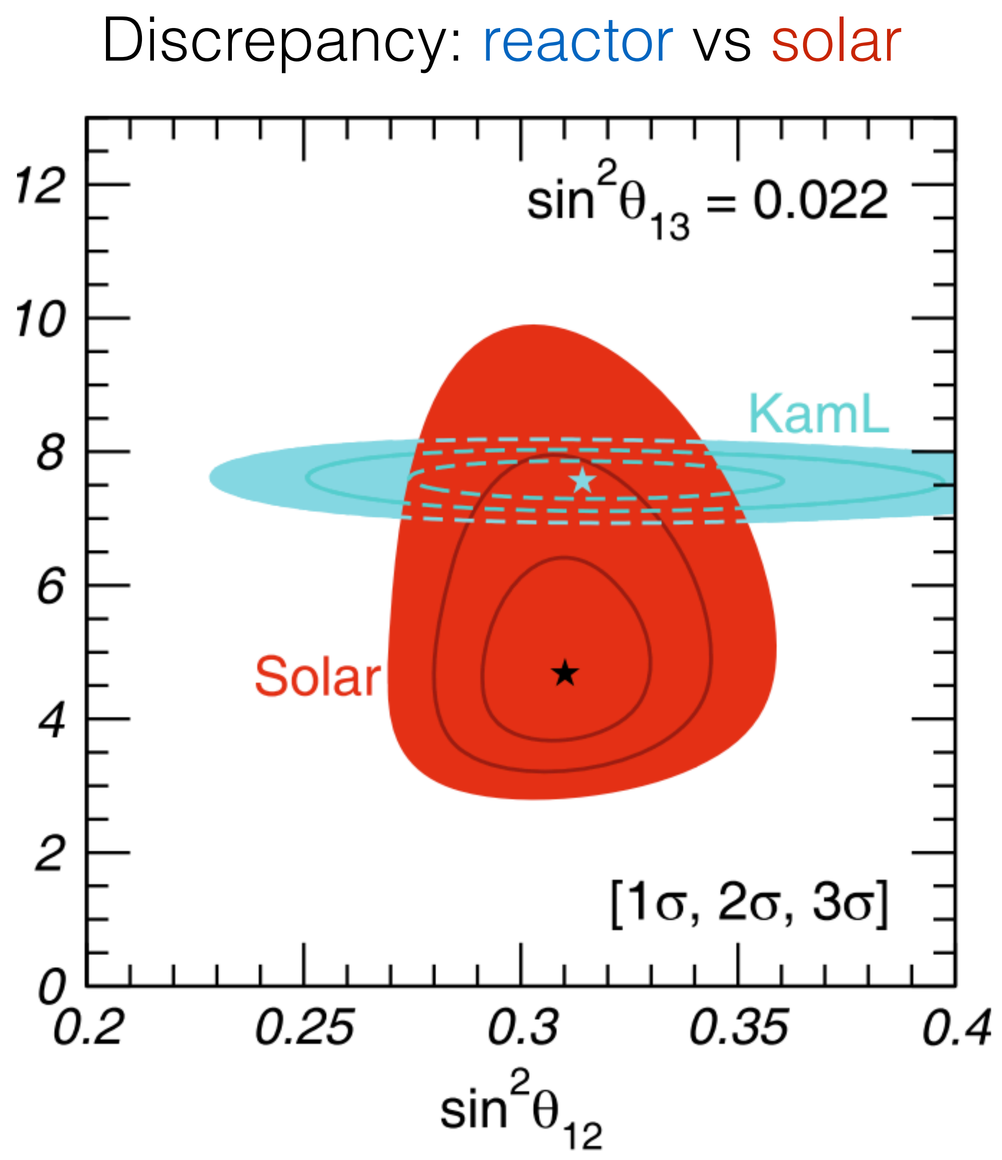
Qian X *et al.* PRD.87.033005. reproduced in F. An et al., "Neutrino physics with JUNO," 2016 pp. 24



[ch10] Why transition region?

- Neutrino oscillation **transition region** not observed yet.
- **2σ Discrepancy** between KamLAND and solar on $\Delta m_{21}{}^2$





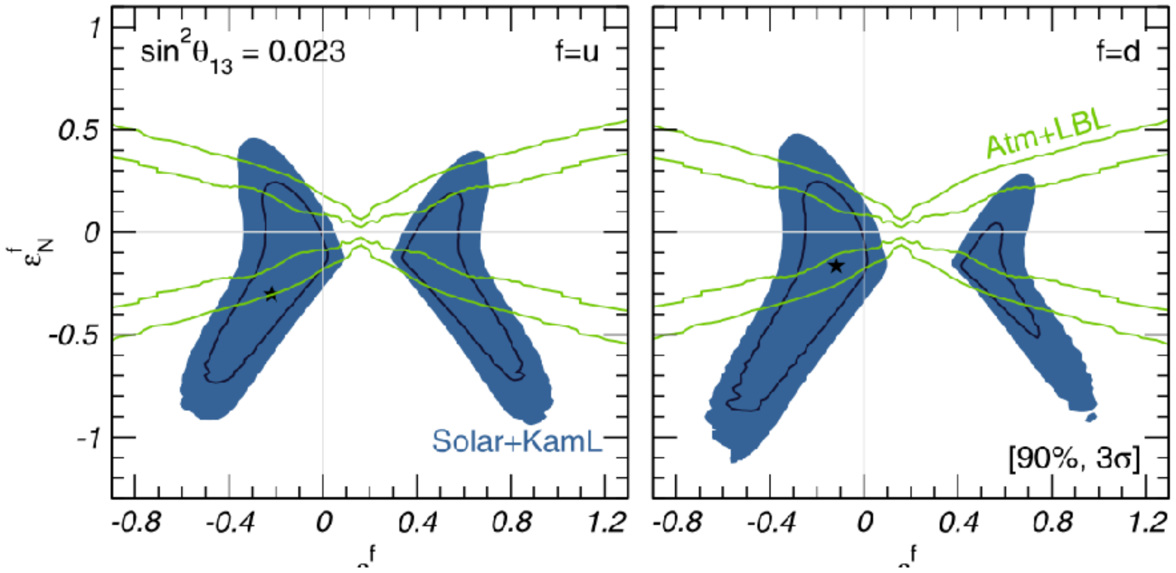
Maltoni et al. Eur. Phys. J. A (2016) 52:87

[ch10] Why transition region?

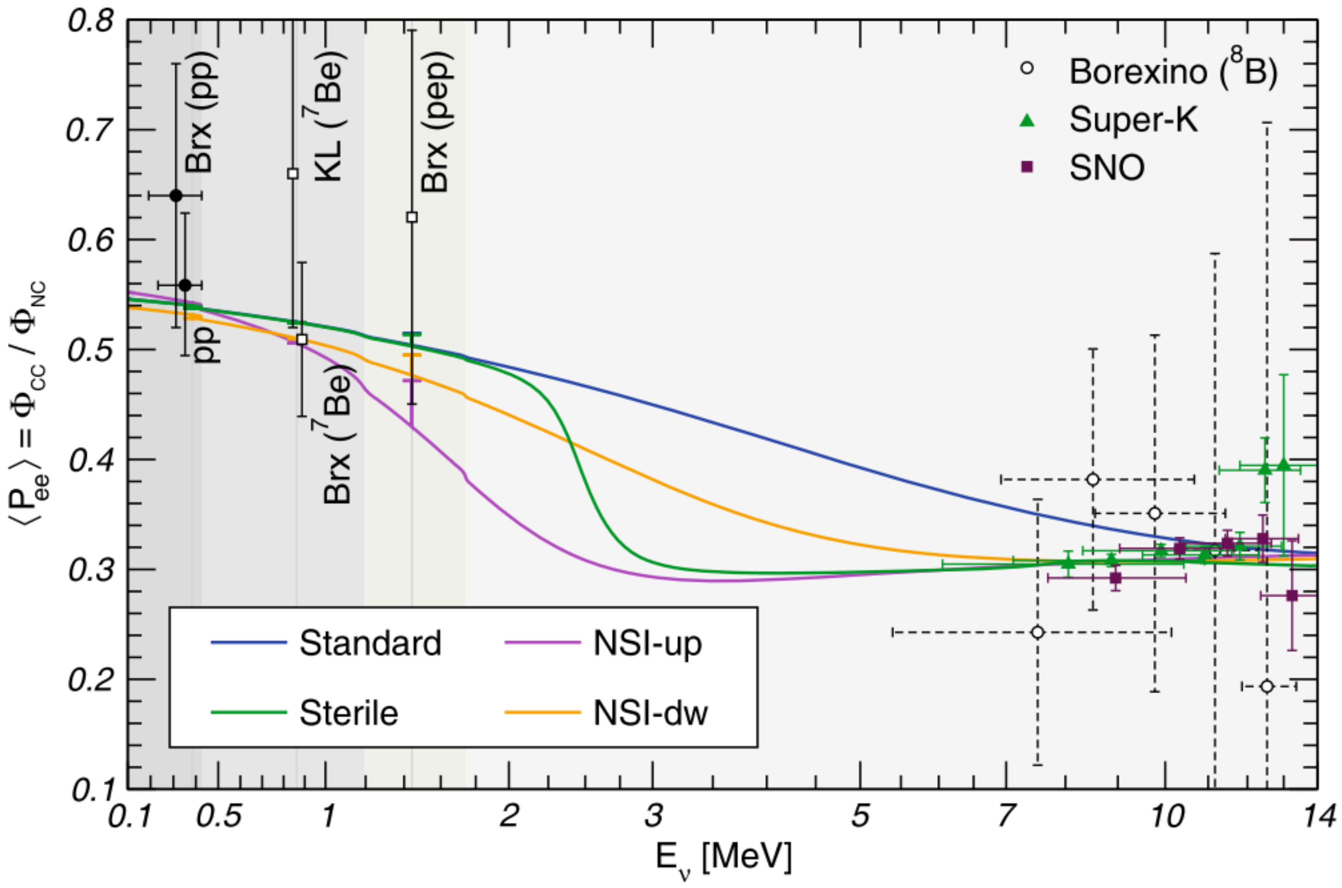
- Transition zone: criteria for new physics (M.M. Guzzo, P.C. de Holanda, O.L.G. Peres 2002)

A. Friedland, C. Lunardini, and C. Peña-Garay, “**Solar neutrinos as probes of neutrino–matter interactions,**” *Phys. Lett. B*, vol. 594, no. 3–4, pp. 347–354, Aug. 2004.
M. . Guzzo, P. . de Holanda, and O. L. . Peres, “**Effects of non-standard neutrino interactions on MSW-LMA solution to the solar neutrino problem**,” *Phys. Lett. B*, vol. 591, no. 1–2, pp. 1–6, Jul. 2004.

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)(\bar{f}\gamma_\mu P f),$$



Maltoni et al. Eur. Phys. J. A (2016) 52:87

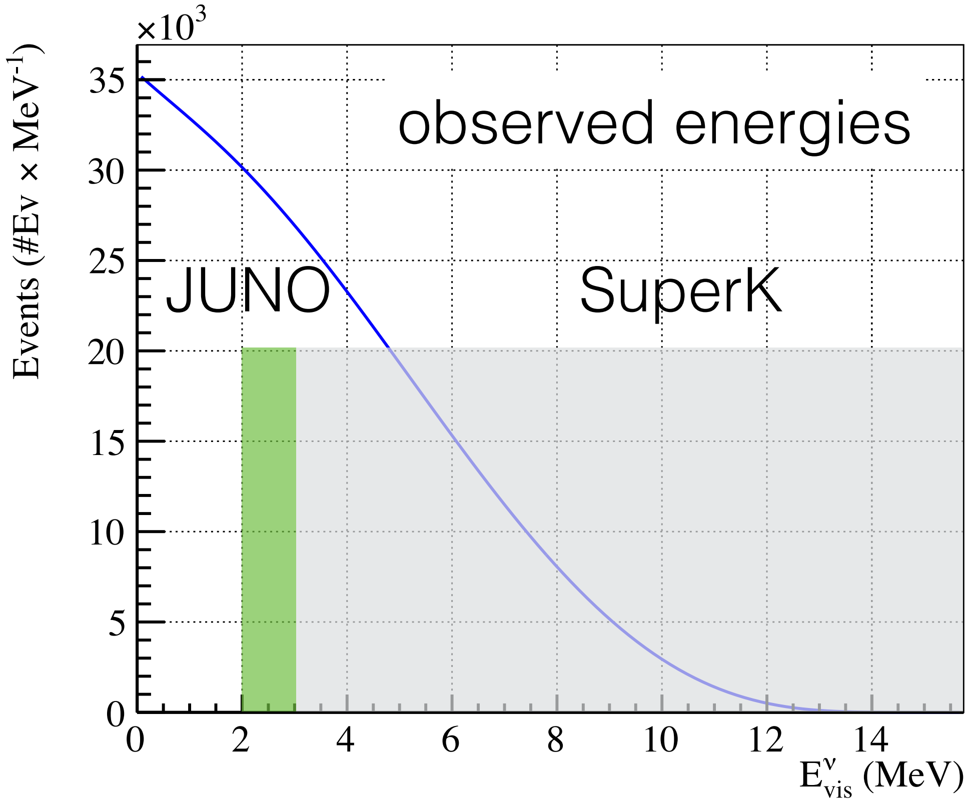


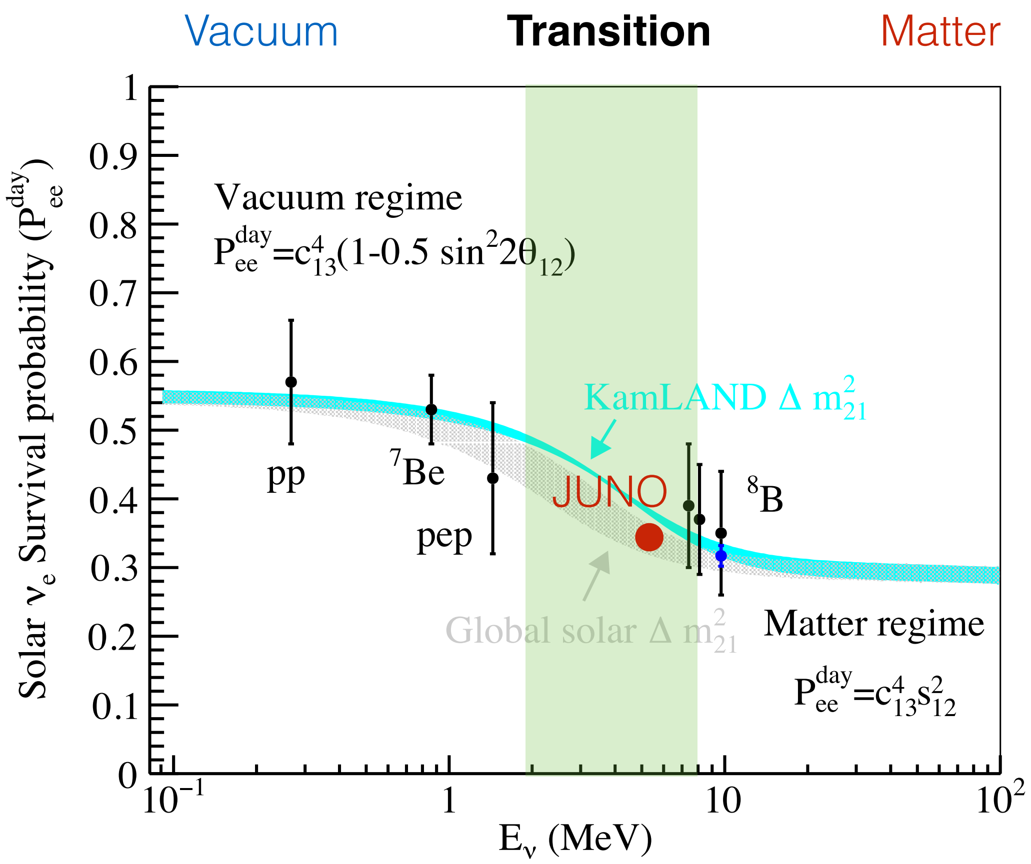
Maltoni et al. Eur. Phys. J. A (2016) 52:87

[ch10] Why JUNO ^{8}B solar neutrinos?

✤ **Can probe transition region.**

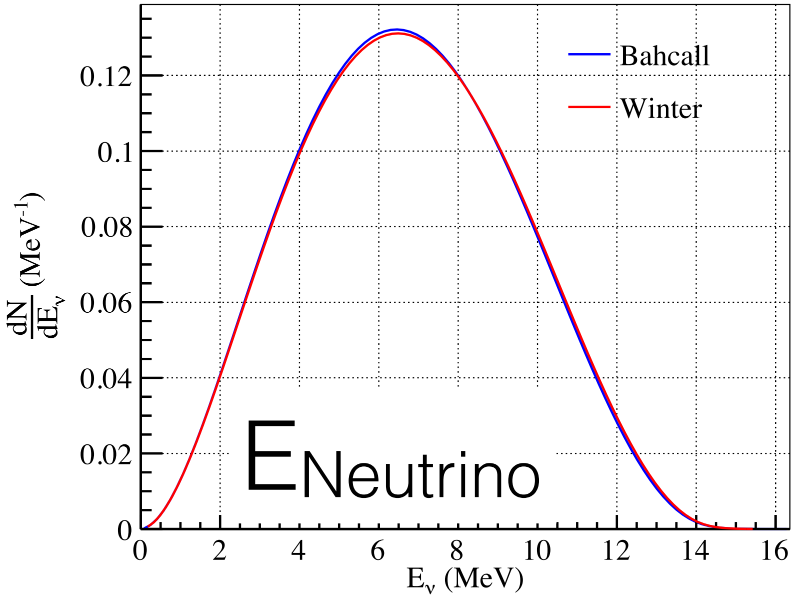
- SuperK/BX: T **3—5** MeV E$_\nu$~7.4 MeV (almost outside the transition region). SuperK: high threshold. Borexino: too small.
- JUNO: T **2—3** MeV E$_\nu$~6.2 MeV (in the transition region) JUNO is big and can cut external backgrounds.





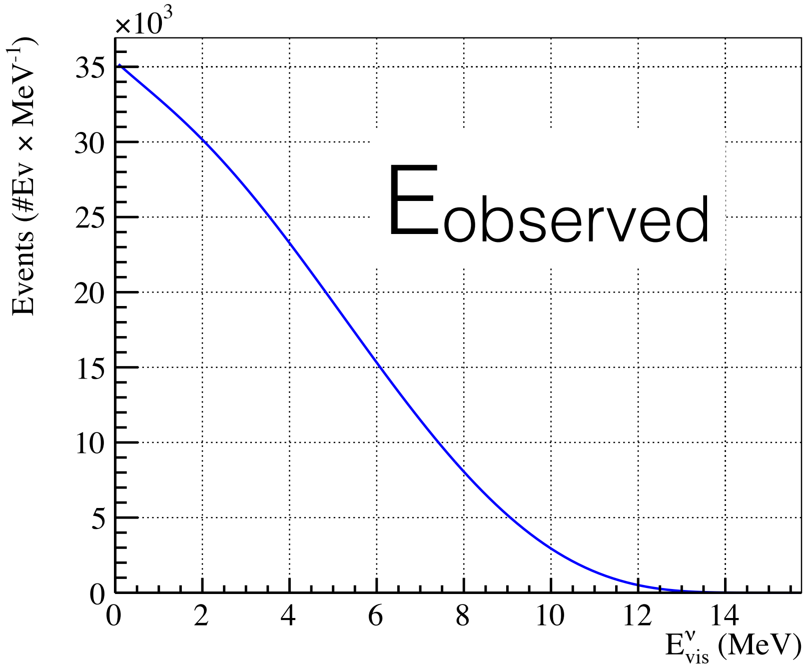
[ch10] Signal and major backgrounds

Elastic scattering signals

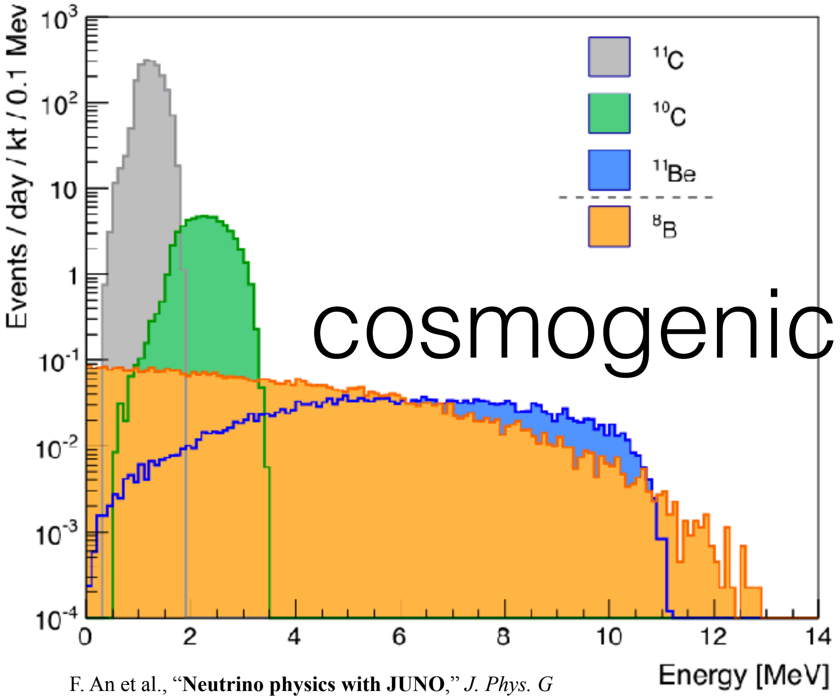


$E_{Neutrino}$

J. N. Bahcall: 10.1103/PhysRevD.51. 6146
W. T. Winter: 10.1103/PhysRevC.73. 025503

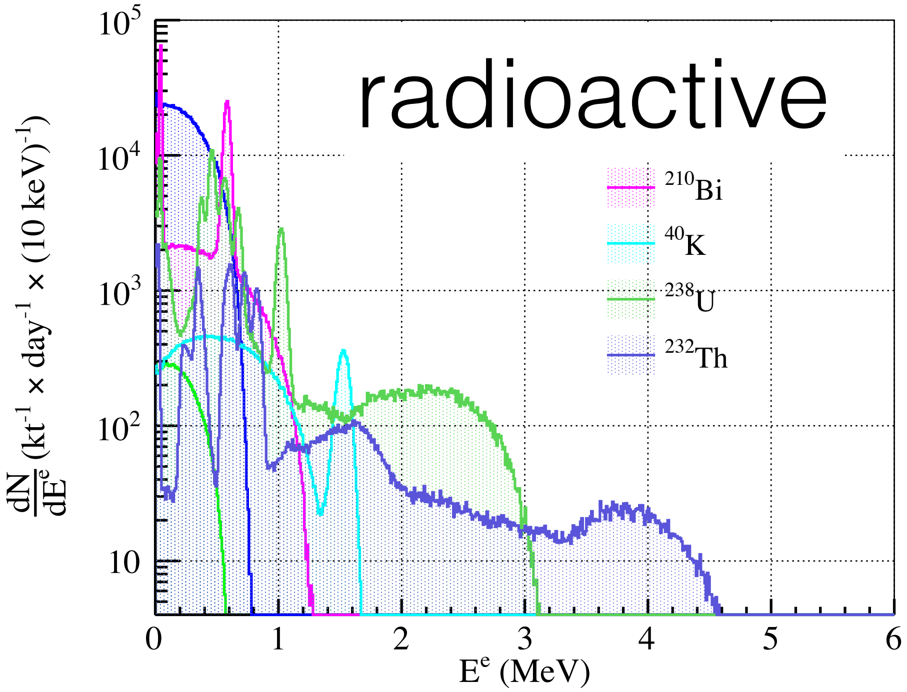


$E_{observed}$



cosmogenic

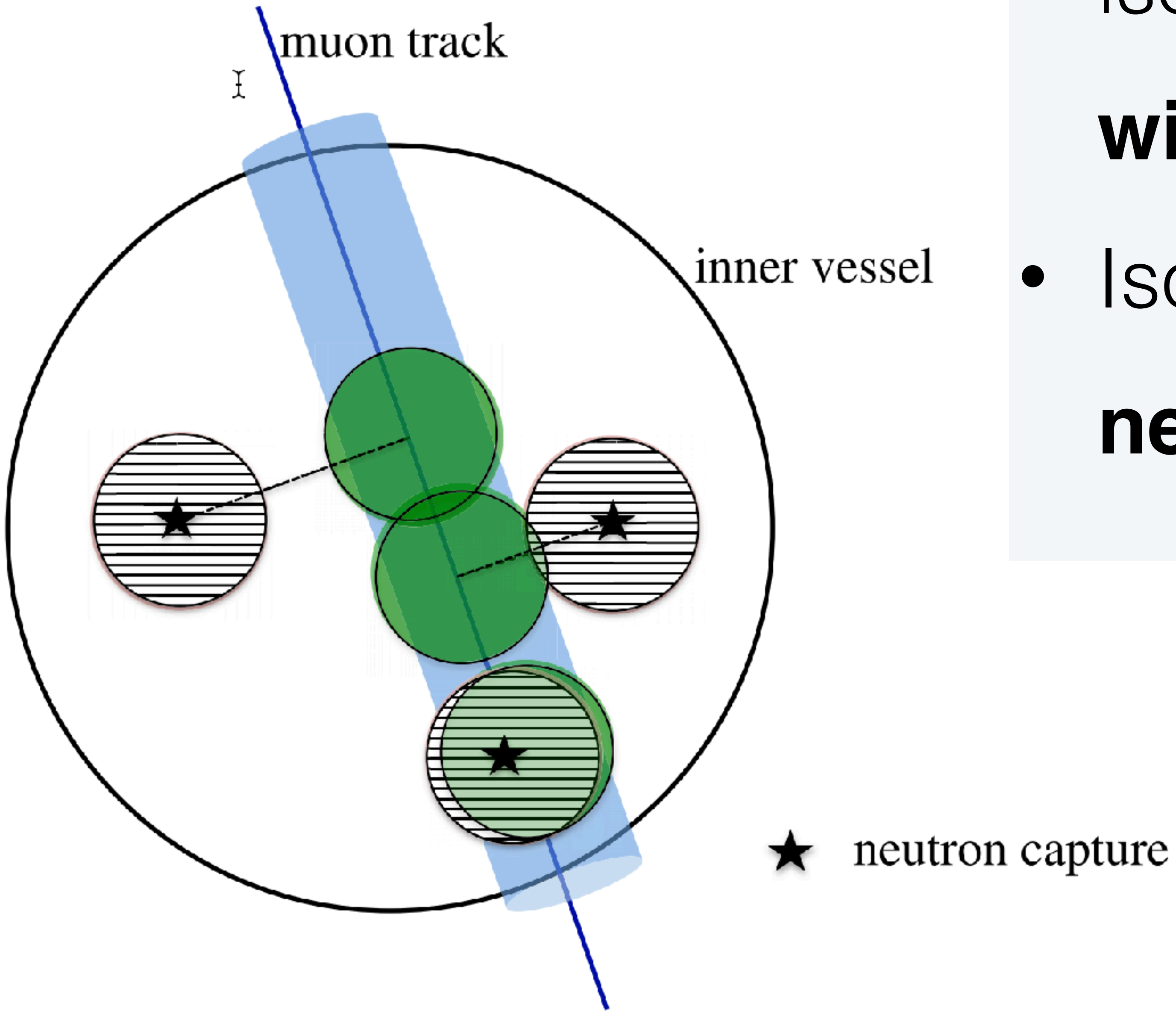
F. An et al., “**Neutrino physics with JUNO**,” *J. Phys. G Nucl. Part. Phys.*, vol. 43, no. 3, p. 030401, 2016.



radioactive

[ch10] cosmogenic: use **TFC**

Three-**F**old-**C**oincidence

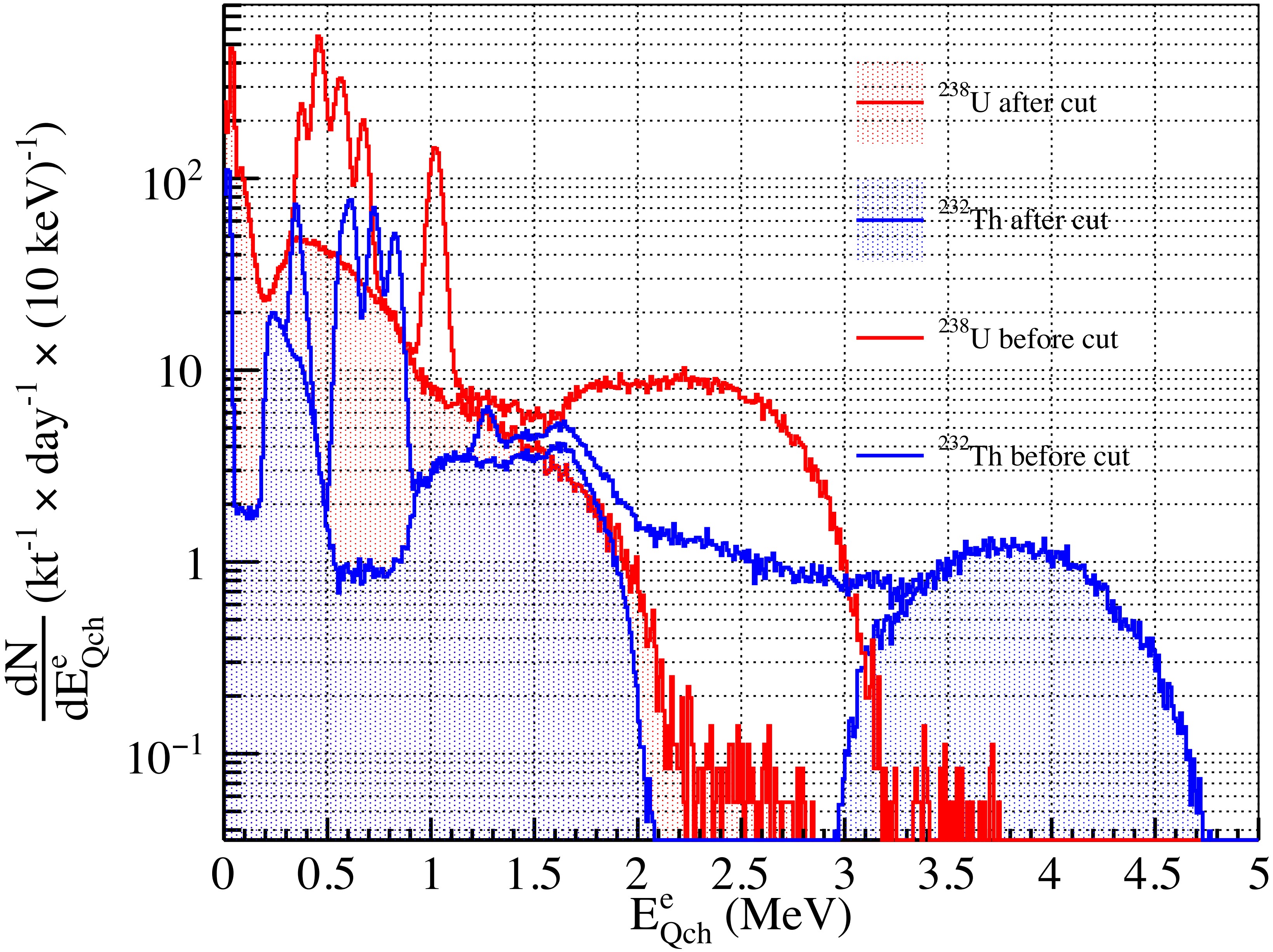


Borexino, “Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy,” Phys. Rev. D - Part. Fields, Gravit. Cosmol., vol. 89, no. 11, pp. 1–68, 2014.

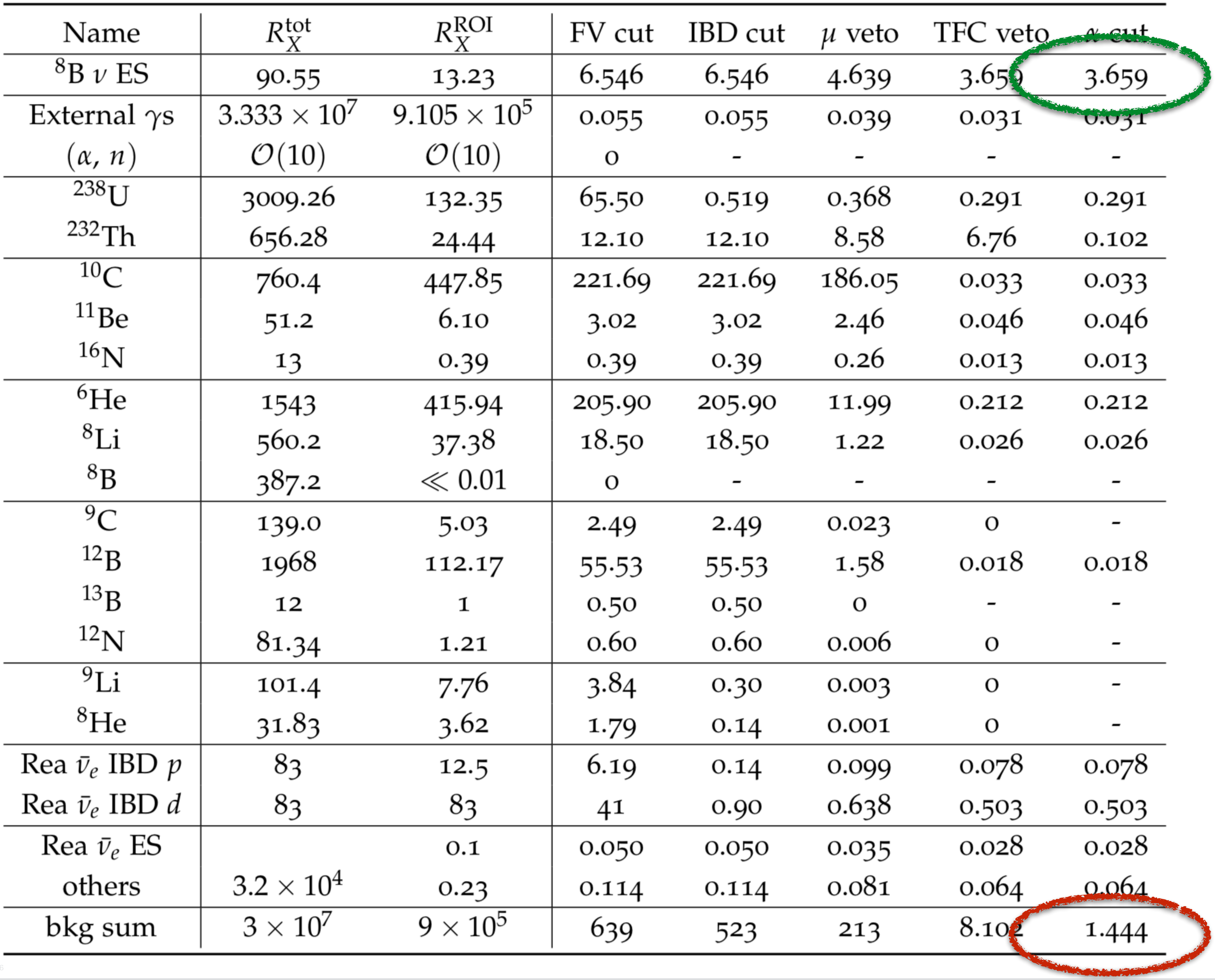
- Production of cosmogenic isotope is usually **associated with one/more neutron**.
- Isotope produced **without neutron can also be rejected**.

[ch10] radioactivity: α/β disc. + coincidence

- By rejecting ^{212}Bi—^{212}Po and ^{214}Bi—^{214}Po, we significantly reduce bkg. in ROI (2~3 MeV)



[ch10] Summary of Signal and Backgrounds



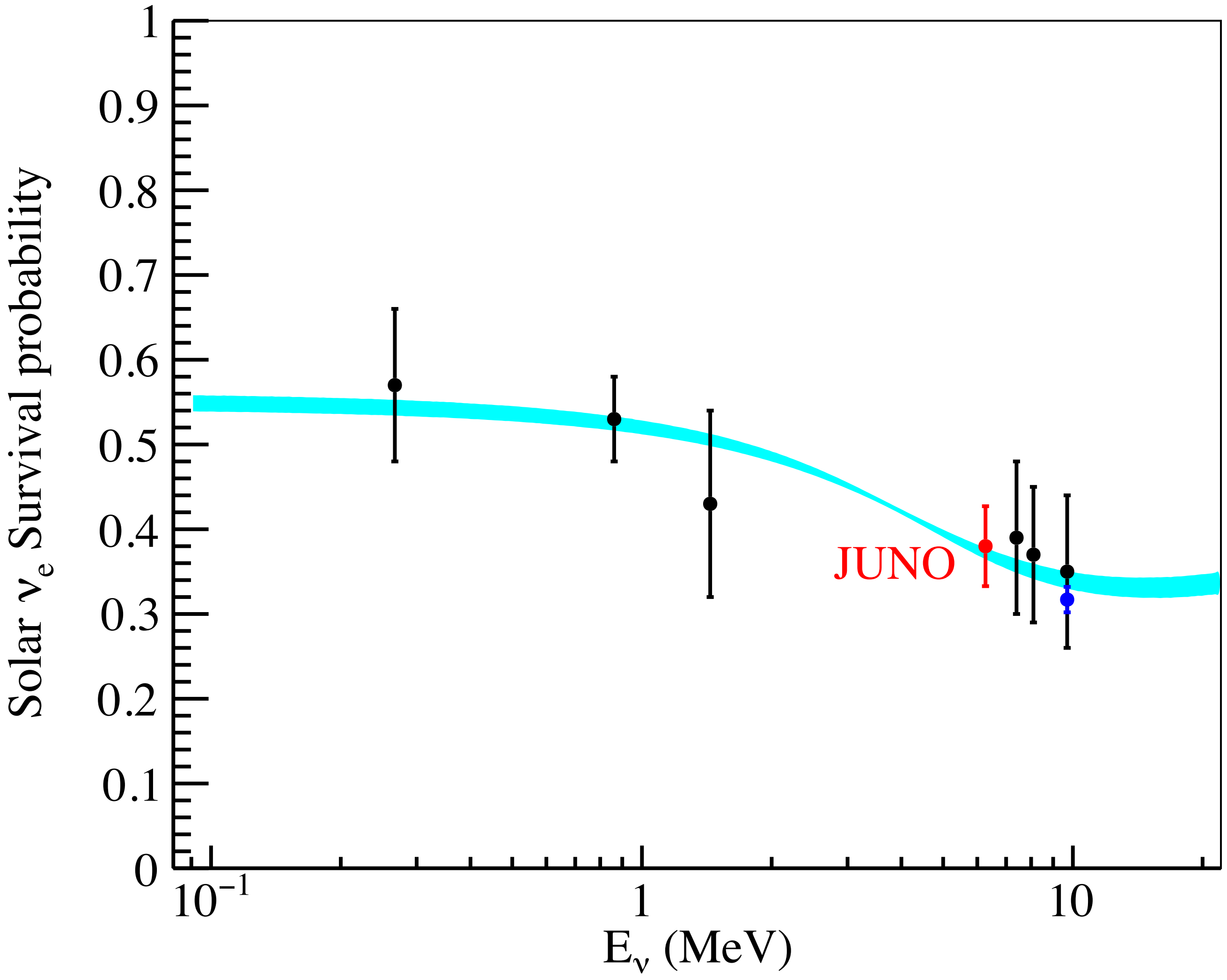
Name	R_X^{tot}	R_X^{ROI}	FV cut	IBD cut	μ veto	TFC veto	α cut
^{8}B ν ES	90.55	13.23	6.546	6.546	4.639	3.659	3.659
External γs	3.333×10^7	9.105×10^5	0.055	0.055	0.039	0.031	0.031
(α, n)	$\mathcal{O}(10)$	$\mathcal{O}(10)$	0	-	-	-	-
^{238}U	3009.26	132.35	65.50	0.519	0.368	0.291	0.291
^{232}Th	656.28	24.44	12.10	12.10	8.58	6.76	0.102
^{10}C	760.4	447.85	221.69	221.69	186.05	0.033	0.033
^{11}Be	51.2	6.10	3.02	3.02	2.46	0.046	0.046
^{16}N	13	0.39	0.39	0.39	0.26	0.013	0.013
^{6}He	1543	415.94	205.90	205.90	11.99	0.212	0.212
^{8}Li	560.2	37.38	18.50	18.50	1.22	0.026	0.026
^{8}B	387.2	$\ll 0.01$	0	-	-	-	-
^{9}C	139.0	5.03	2.49	2.49	0.023	0	-
^{12}B	1968	112.17	55.53	55.53	1.58	0.018	0.018
^{13}B	12	1	0.50	0.50	0	-	-
^{12}N	81.34	1.21	0.60	0.60	0.006	0	-
^{9}Li	101.4	7.76	3.84	0.30	0.003	0	-
^{8}He	31.83	3.62	1.79	0.14	0.001	0	-
Rea $\bar{\nu}_e$ IBD p	83	12.5	6.19	0.14	0.099	0.078	0.078
Rea $\bar{\nu}_e$ IBD d	83	83	41	0.90	0.638	0.503	0.503
Rea $\bar{\nu}_e$ ES		0.1	0.050	0.050	0.035	0.028	0.028
others	3.2×10^4	0.23	0.114	0.114	0.081	0.064	0.064
bkg sum	3×10^7	9×10^5	639	523	213	8.102	1.444

DocDB 1486

S/B = 2.5

[ch10] expected P_{ee}

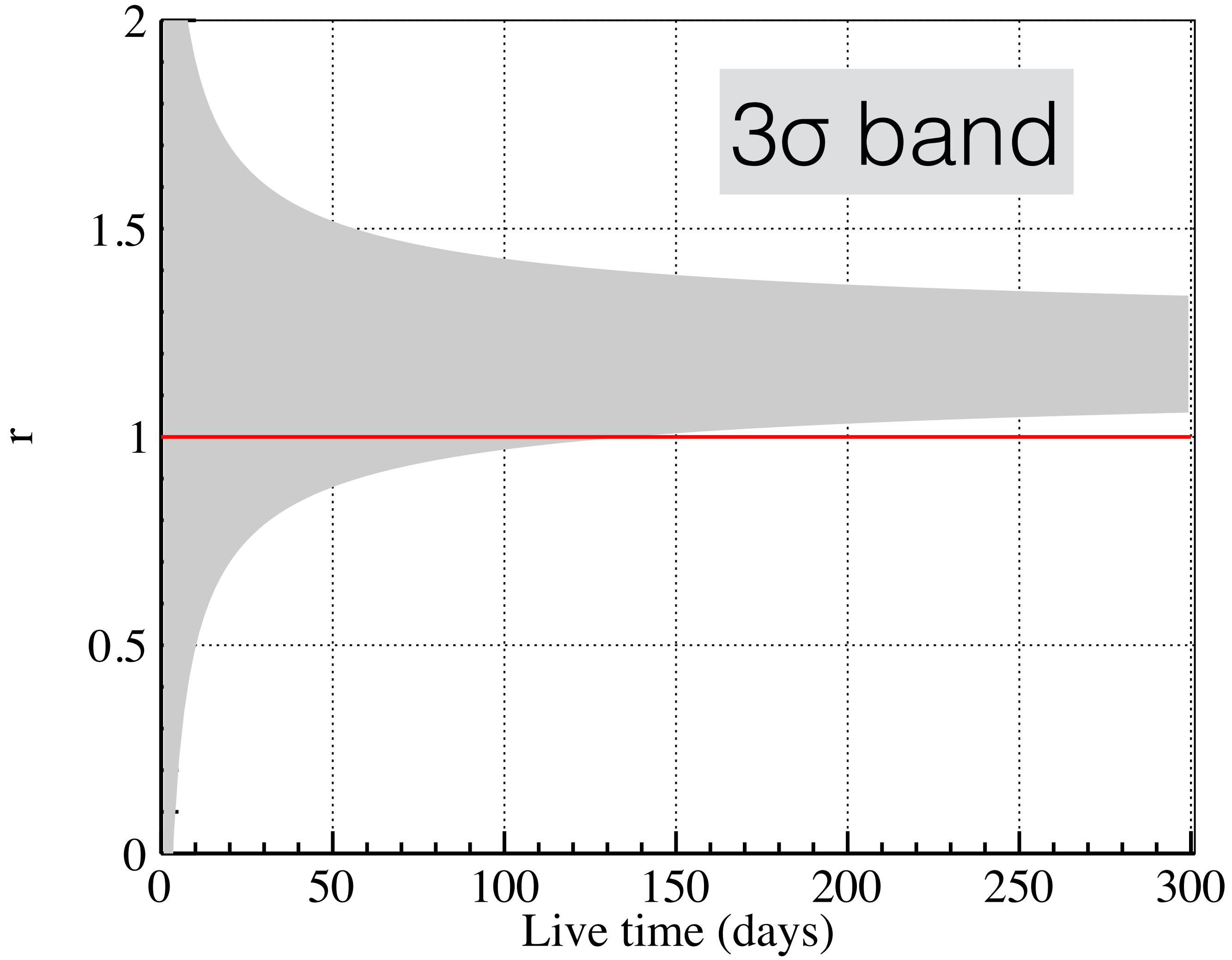
- ROI: Kinetic energy of electron ***T*** ~ [2, 3] MeV
- Average energy of contribution neutrinos: 6.18 MeV



1 year data: 14%
3.2% rate precision
12% theory uncertainty

[ch10] Sensitivity to upturn

- Define ratio of avg P_{ee} between JUNO and Super-K
- r>1: evidence of upturn

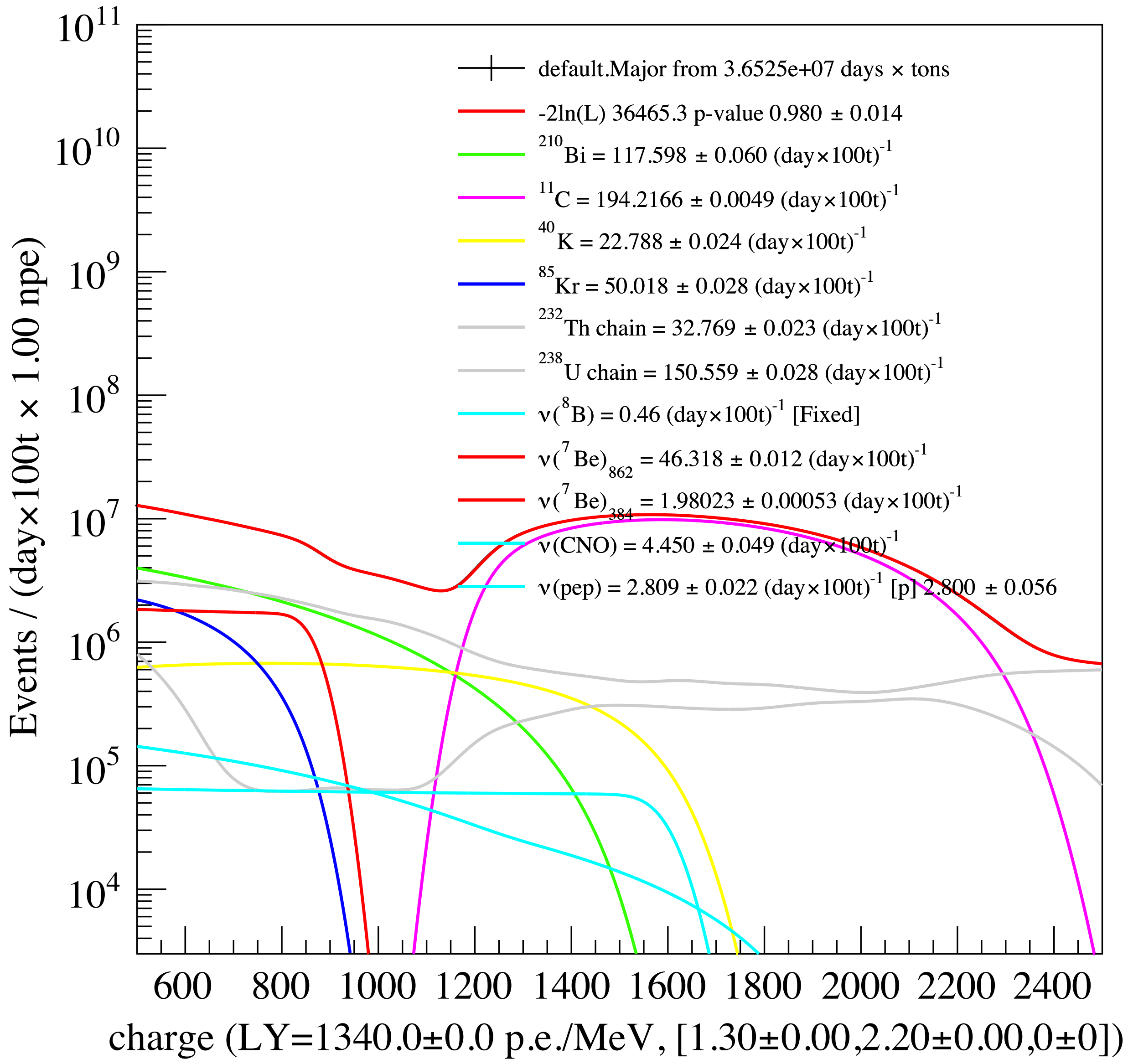


$$r^{\mathrm{SK/JUNO}} = \frac{P_{ee}(\text{Super-K})}{P_{ee}(\text{JUNO})}$$

140 days of data:
>3σ rejection of H_0

[ch11] ^{7}Be solar neutrinos with JUNO

- assuming **0.5%** energy scale precision
  - ν(^{7}Be): 1± ~0% (stat.) ± 7% (sys.)

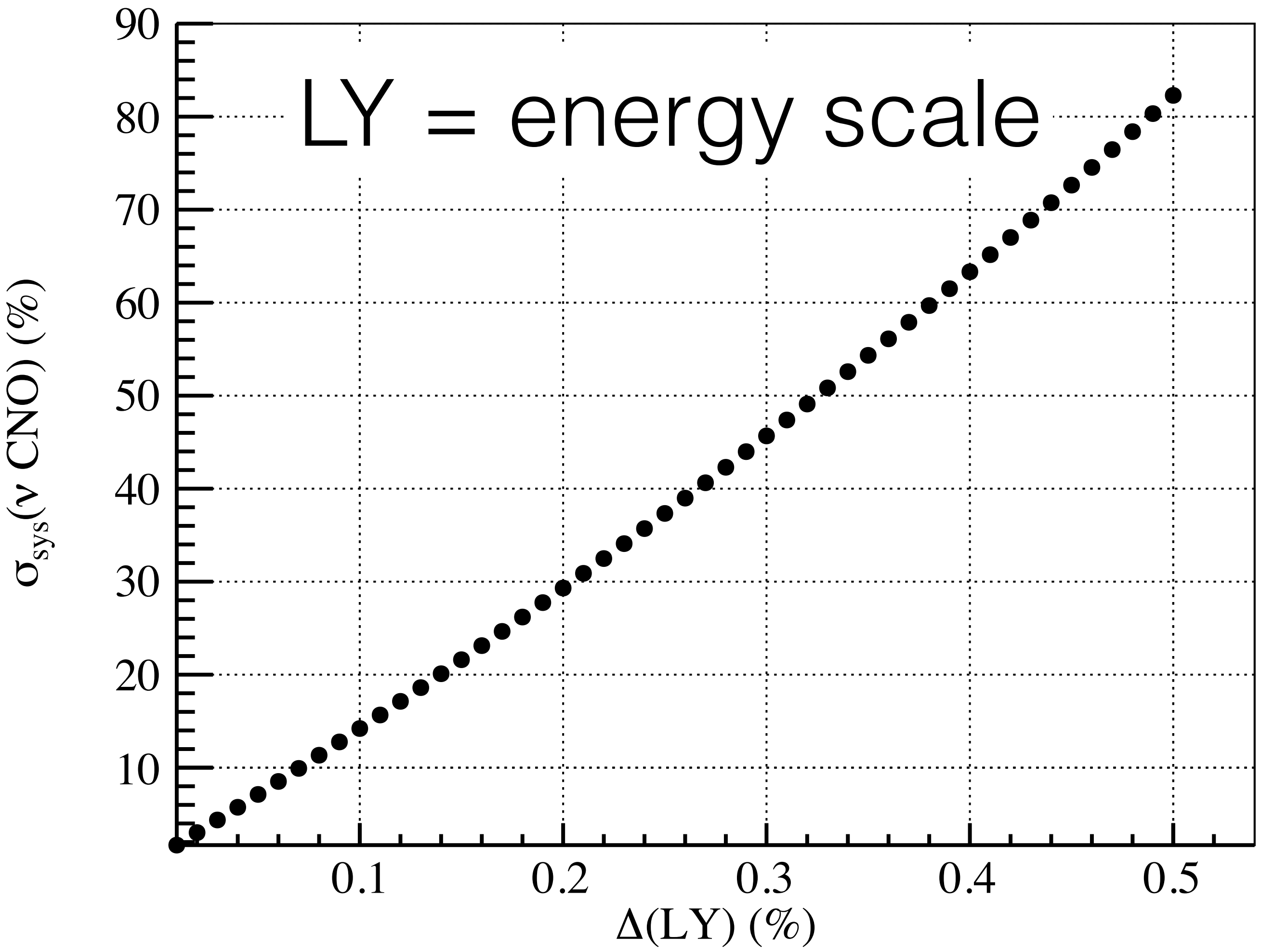


10 years data

[ch11] CNO solar neutrinos with JUNO

- CNO: dominated by systematic uncertainty.
- 0.1% precision energy scale: σ(CNO) can reach 13%

✤ ^{210}Bi not constrained. Borexino use a different strategy, will be explained later.



10 years data

Summary: Solar neutrinos with JUNO

- Can detect ^{8}B solar ν in 2~3 MeV: transition region, NSI
- Can detect ^{7}Be solar ν with 7% precision
- Can detect CNO with 13% precision -> 0.1% energy scale precision (challenging)

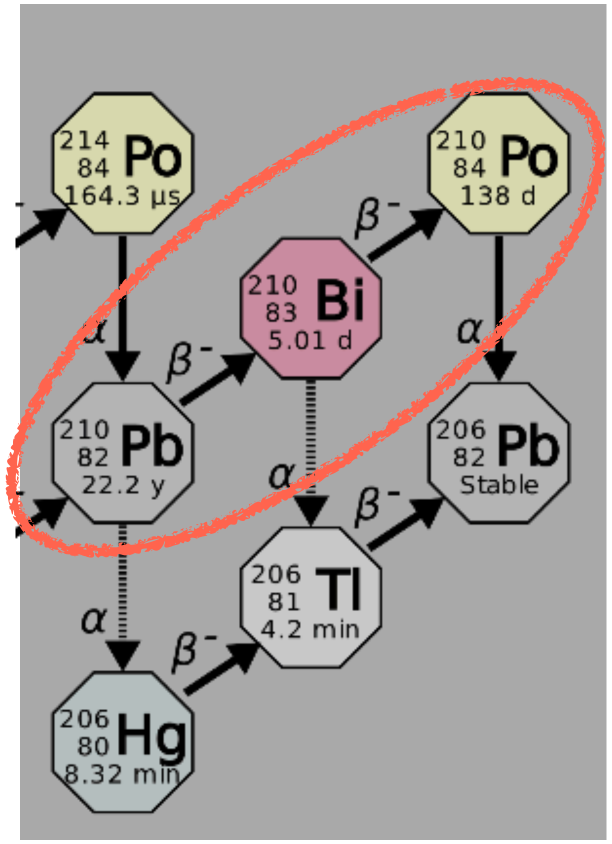
Future: CNO solar neutrinos

Chapter 7, 8

CNO with Borexino

- Challenge of CNO: almost same shape of ^{210}Bi. **Only know CNO+^{210}Bi**

- Borexino: to measure CNO, we measure ^{210}Bi



- When ^{210}Pb—^{210}Bi—^{210}Po are in secular equilibrium, R(^{210}Bi)=R(^{210}Po)

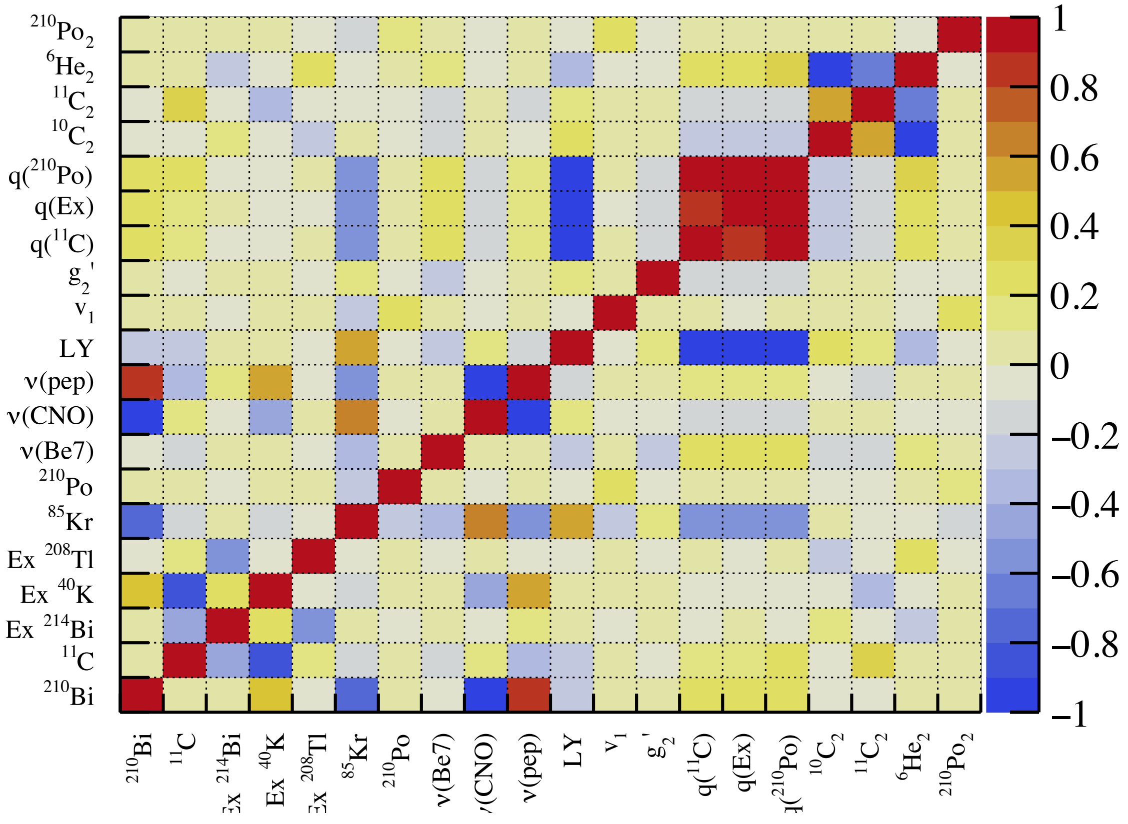
- R(^{210}Po) can be measured easily. α decay has longer scintillation time.

[ch 7] CNO sensitivity

- How good we can reach if ^{210}Bi is constrained?
  - **toy MC method**: generate lots of pseudo-experiment spectra, fit them, see the width of fit result the distribution
  - Fit the Asimov dataset, and read the **fit error** directly.
  - **Simple counting method**: we know R(sum) = R(CNO) +R(^{210}Bi)+R(pep) from counting, then R(CNO) = R(sum) - R(^{210}Bi) - R(pep)
  - **Correlation matrix method**: we know R(CNO)+R(^{210}Bi) +R(pep) from fit output correlation matrix, then R(CNO) = R(sum) - R(^{210}Bi) - R(pep)

[ch 7] CNO: correlation matrix

- Fit results depend on your dataset. They are random variables. They are test statistics.
- We can define correlation matrix of random variables
- By linearly combining random variables (diagonalizing the correlation matrix), we can find independent variables.



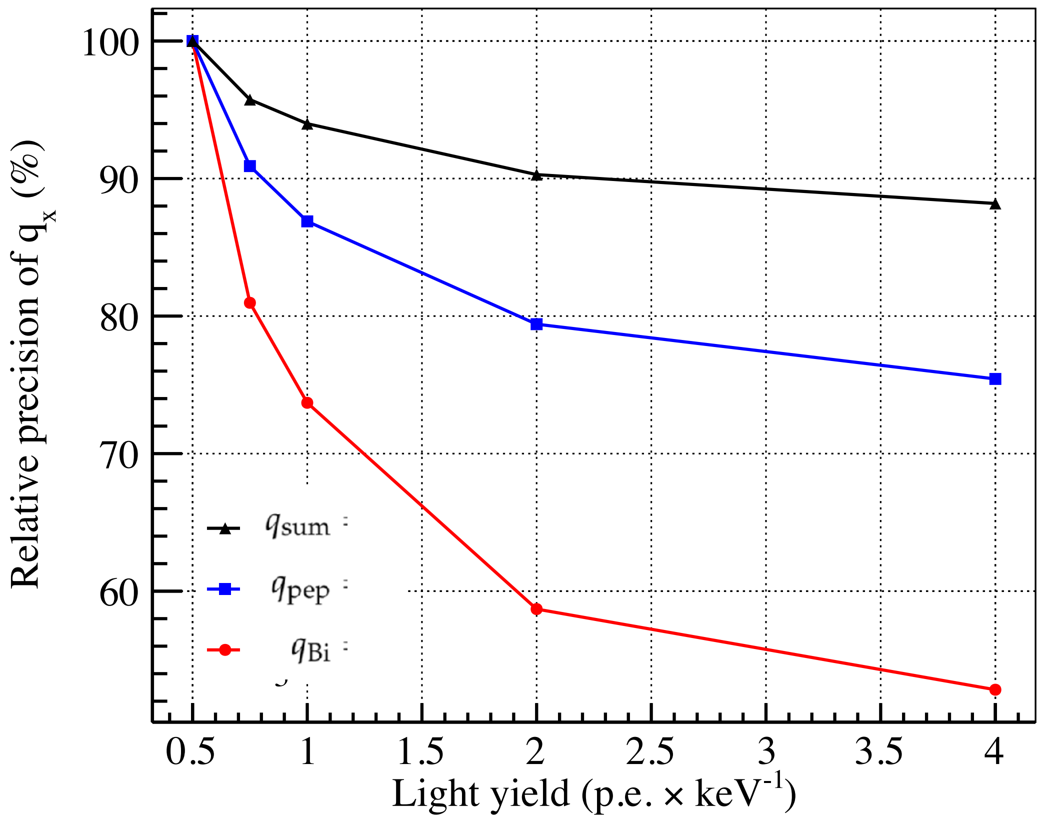
What we found

R(CNO) + **0.6** R(^{210}Bi) + **2.6** R(pep)

$$
\begin{aligned}
q_{\mathrm{sum}} &= R_{\nu(\mathrm{CNO})} + 0.57 R_{^{210}\mathrm{Bi}} + 2.58 R_{\nu(\mathrm{pep})} = 21.87 \pm 0.81 \\
q_{\mathrm{pep}} &= R_{\nu(\mathrm{CNO})} + 1.05 R_{^{210}\mathrm{Bi}} - 0.62 R_{\nu(\mathrm{pep})} = 18.28 \pm 2.56 \\
q_{\mathrm{Bi}} &= R_{\nu(\mathrm{CNO})} - 1.05 R_{^{210}\mathrm{Bi}} - 0.16 R_{\nu(\mathrm{pep})} = -11.59 \pm 23.11\,,
\end{aligned}
$$

[ch 7] physics meaning of 3 quantities

- Similar coefficients found for “**sum**”.
- Precision of q_{pep} and q_{Bi} improves with energy resolution
- **sum** is precise. q_{pep} is worse. almost no sensitivity on q_{Bi}



$$
\begin{aligned}
q_{\text{sum}} &= R_{\nu(\text{CNO})} + 0.57 R_{^{210}\text{Bi}} + 2.58 R_{\nu(\text{pep})} = 21.87 \pm 0.81 \\
q_{\text{pep}} &= R_{\nu(\text{CNO})} + 1.05 R_{^{210}\text{Bi}} - 0.62 R_{\nu(\text{pep})} = 18.28 \pm 2.56 \\
q_{\text{Bi}} &= R_{\nu(\text{CNO})} - 1.05 R_{^{210}\text{Bi}} - 0.16 R_{\nu(\text{pep})} = -11.59 \pm 23.11\,,
\end{aligned}
$$

[ch 7] If we measured ^{210}Bi..

- In summary: different methods converge to the fact that we just just counting number of events (**CNO** + **^{210}Bi** + **pep**). Constrain **^{210}Bi** and **pep** we get **CNO**.

- Assume we measure ^{210}Bi within 10%..

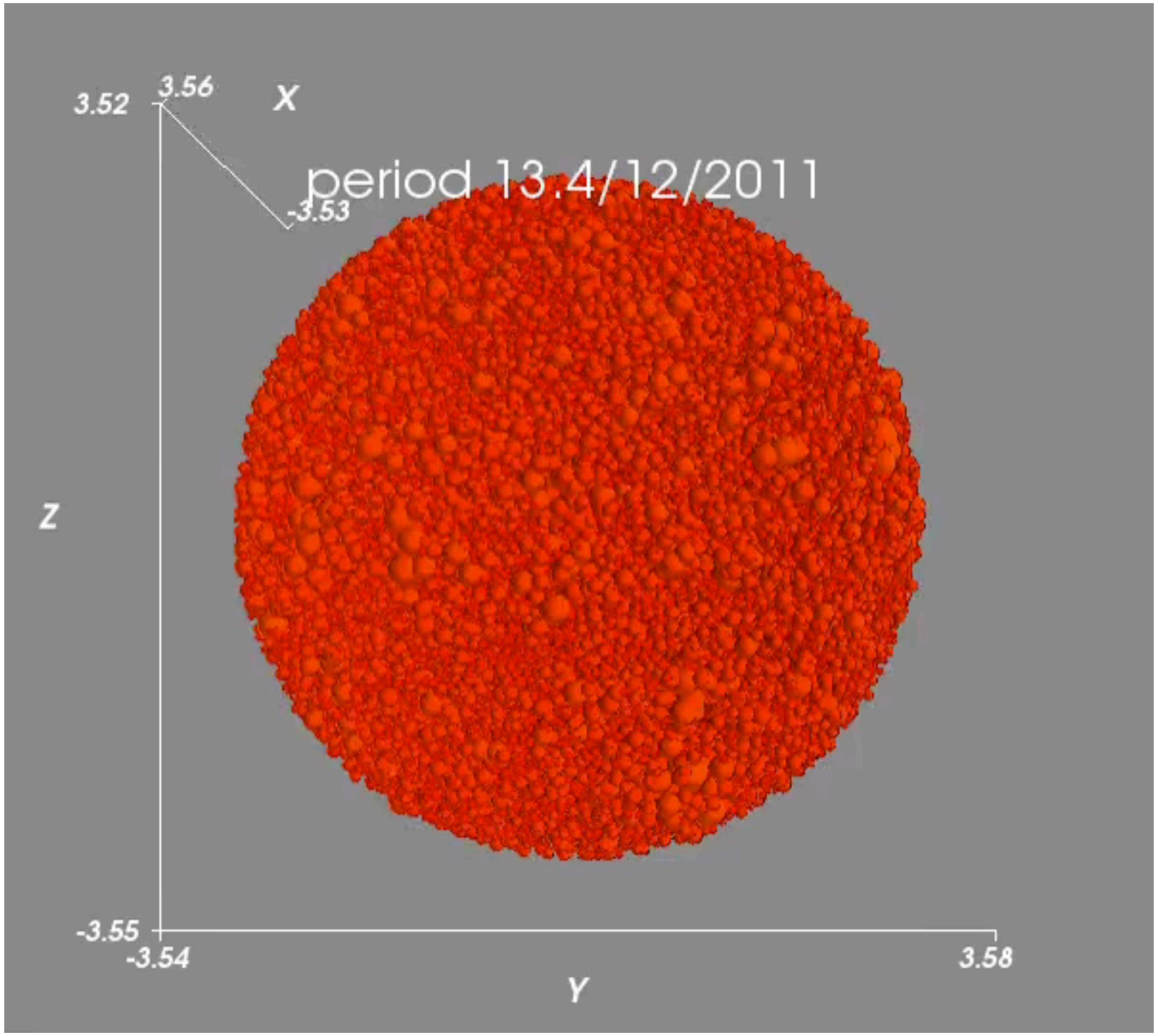
  - Constrain v(pep) within 2%.

  - In case of HZ: median (50% case) sensitivity is **3.9σ**

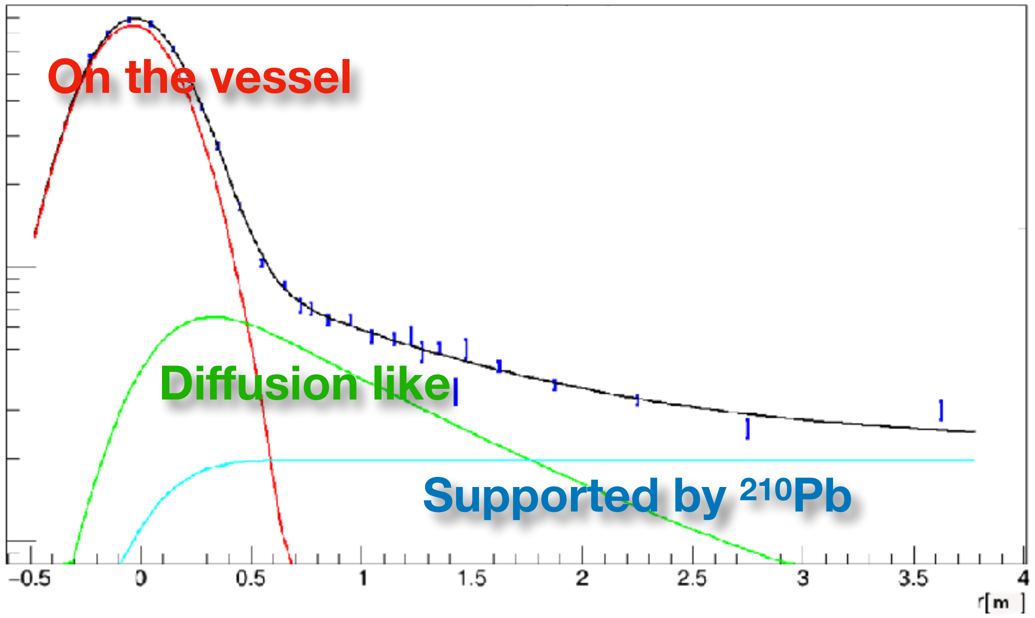
  - In case of LZ: median (50% case) sensitivity is **2.8σ**

[ch 8] Let’s measure ^{210}Bi in data

- Challenge: ^{210}Po brought by convection from outside



Lots of ^{210}Po are brought into the center by the convection motion



[ch 8] Thermal stratification to stop convection

Before insulation

During insulation

- 20 cm Rockwool dressed to maximize the temperature gradient and stabilize the detector's stratification
- **Detector** wide and **experiment hall** wide Heating system

Thermal insulations in a nutshell

Borexino with Rockwool

From F. Calaprice's talk on TAUP 2017

VS

The polar bear

Thermal insulations in a nutshell

k = 0.03 W/m²/K

k = 0.069±0.015 W/m²/K

Scholander PF, Walters V, Hock R, Irving L. 1950. Body insulation of some Arctic and tropical mammals and birds. Biological Bulletin 99: 225–236.

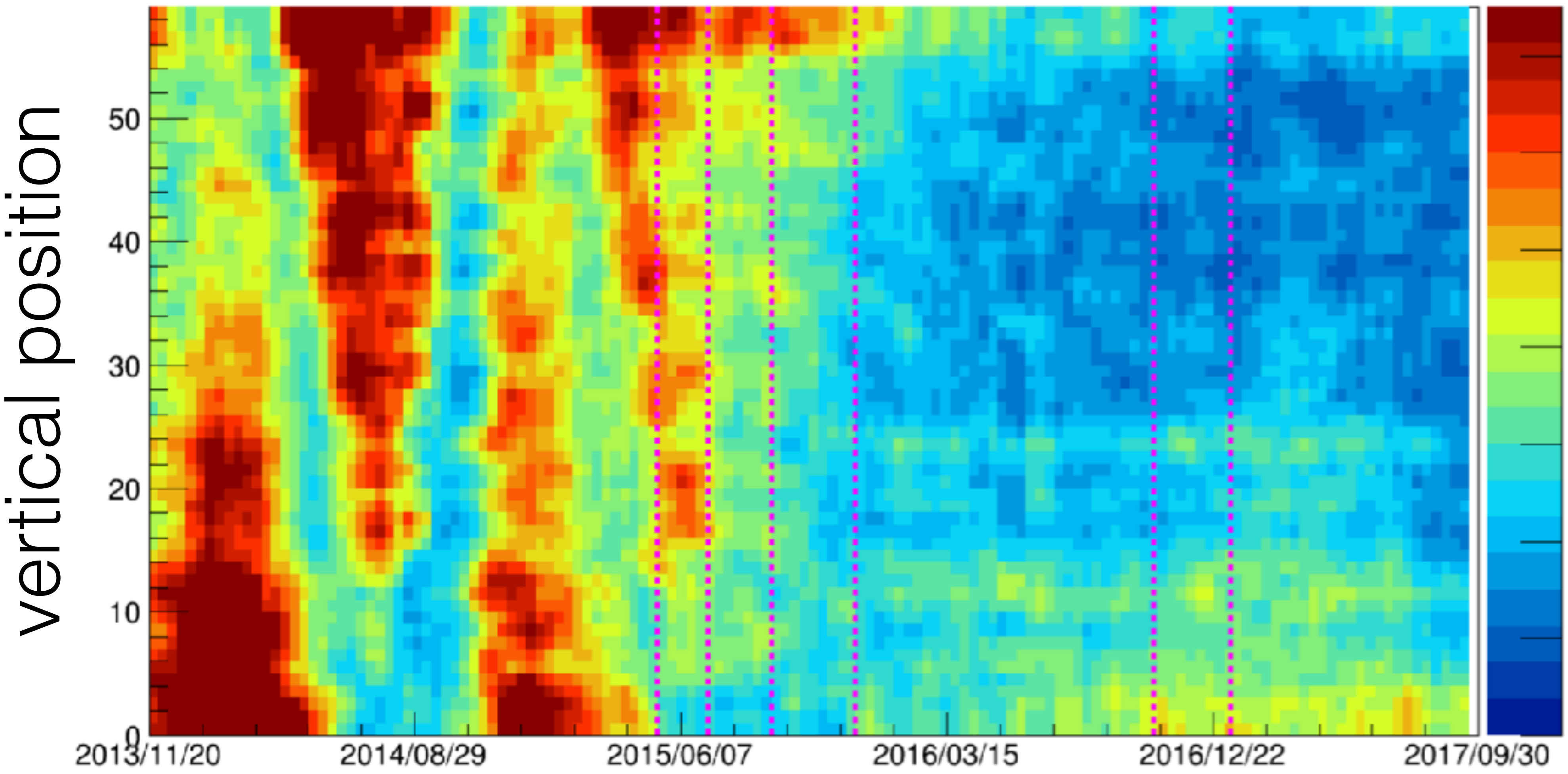
From F. Calaprice's talk on TAUP 2017

VS

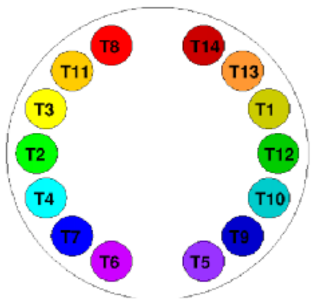
From wikipedia

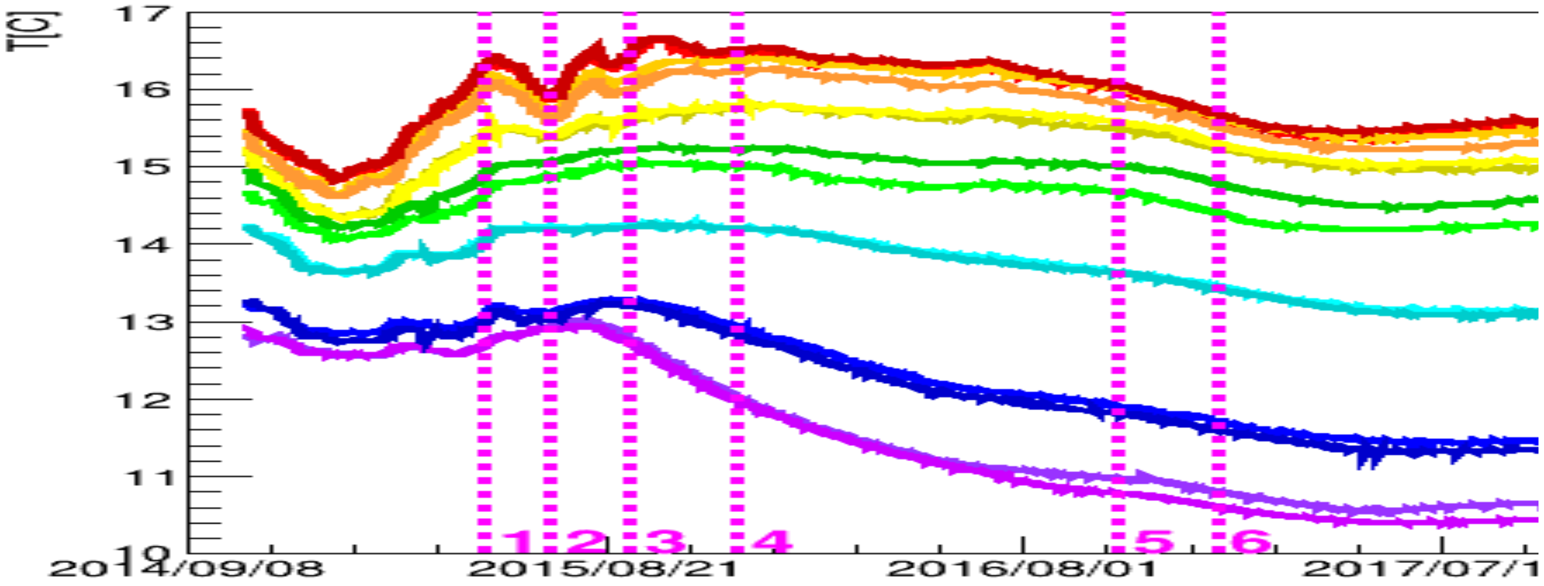
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

[ch 8] Thermal stratification to stop convection



^{210}Po vs z





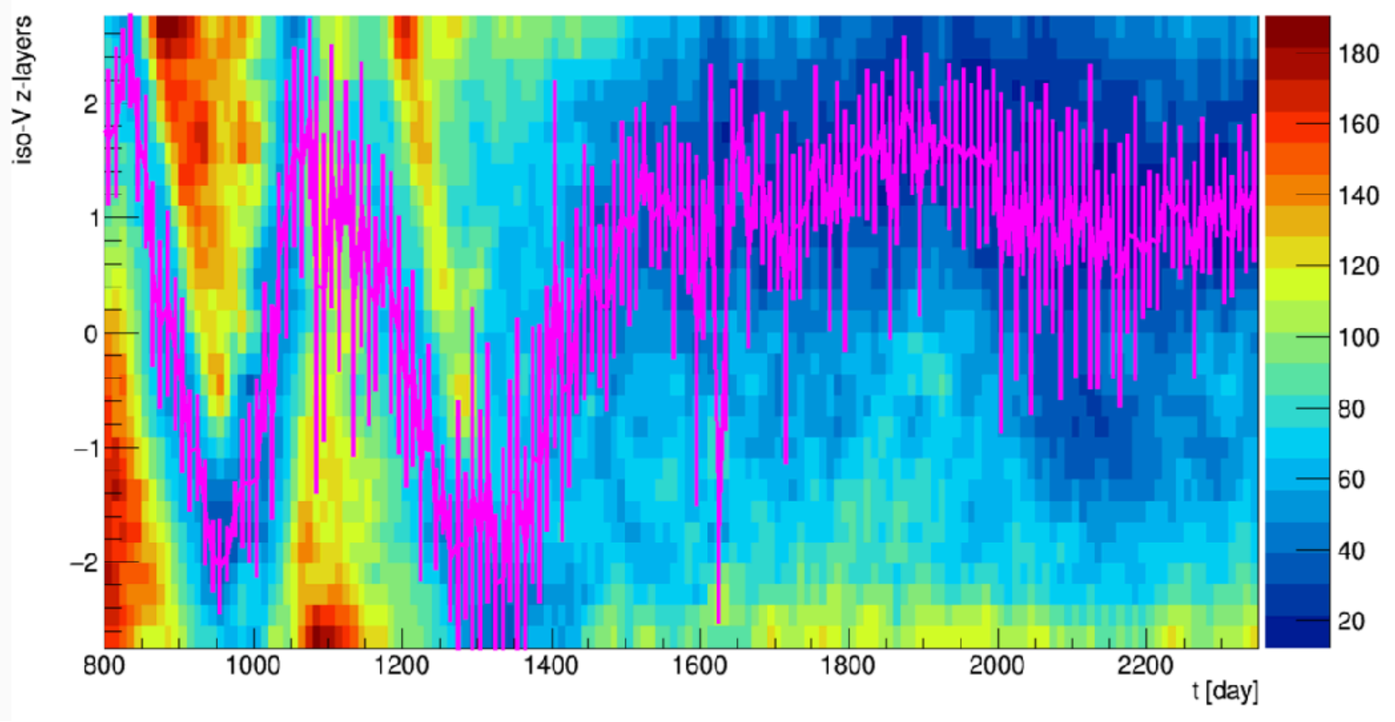
temperature vs z

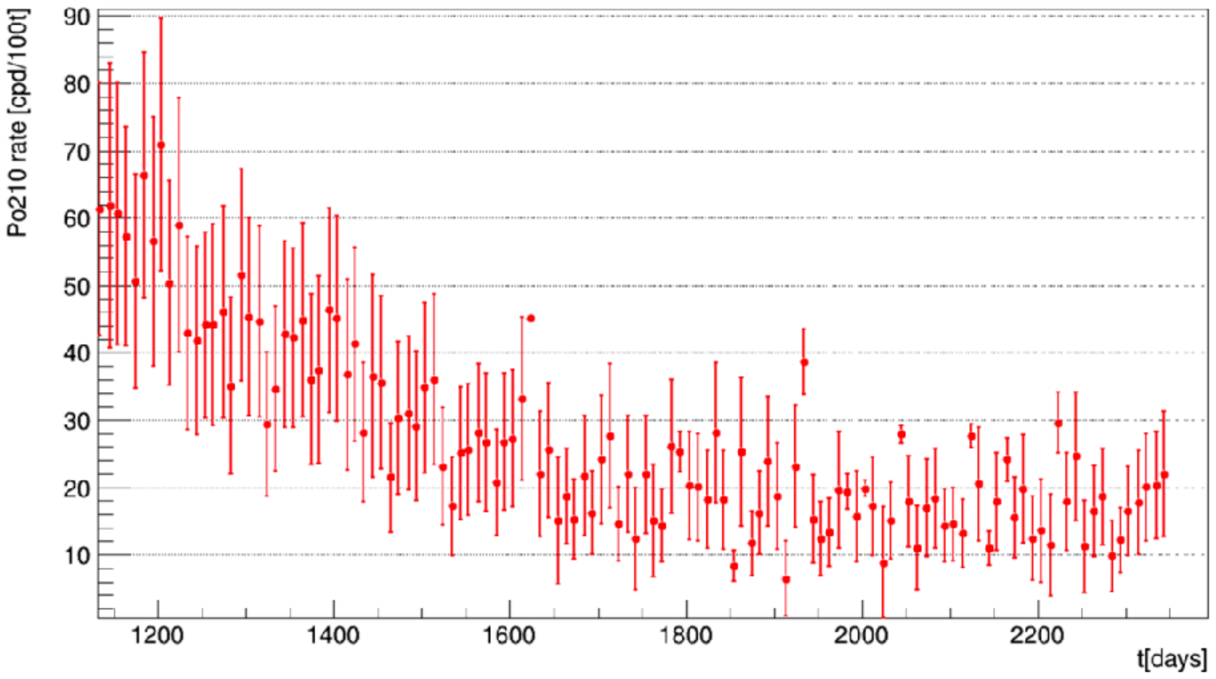
[ch 8] Get rid of migration ^{210}Po

- Follow the minimum
- Contribution of convection vanishes

$$\frac{\partial X_{\text{Bi}}}{\partial t} = X_{\text{Pb}} \cdot \lambda_{\text{Pb}} - X_{\text{Bi}} \cdot \lambda_{\text{Bi}} + \nabla \cdot (D_{\text{Bi}} \cdot \nabla X_{\text{Bi}} - \mathbf{v} X_{\text{Bi}})$$

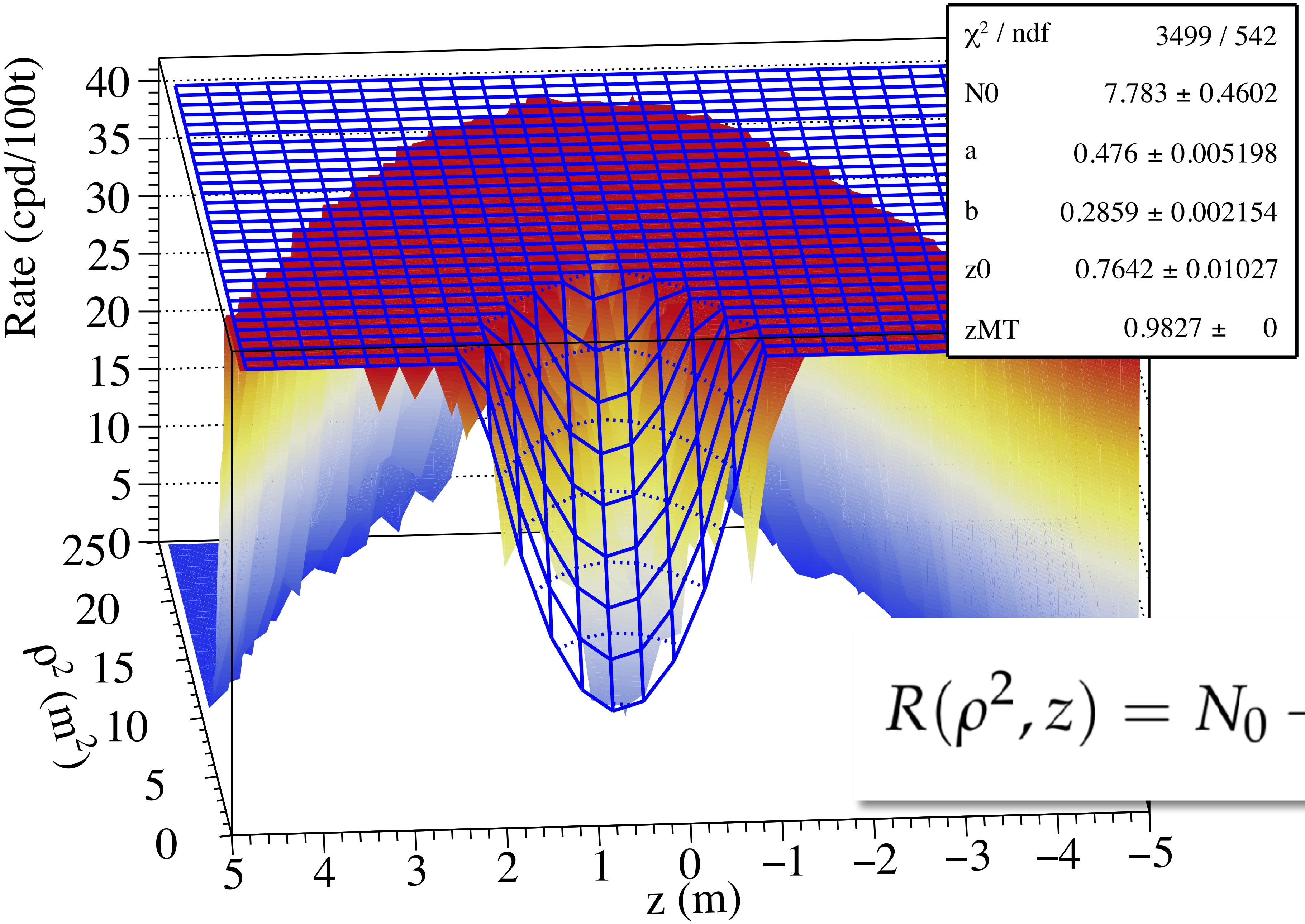
$$= X_{\text{Bi}} \cdot \lambda_{\text{Bi}} - X_{\text{Po}} \cdot \lambda_{\text{Po}} + D_{\text{Po}} \nabla^2 X_{\text{Po}}$$





[ch 8] Get rid of migration ^{210}Po

- Approximate local ^{210}Po density with paraboloid function

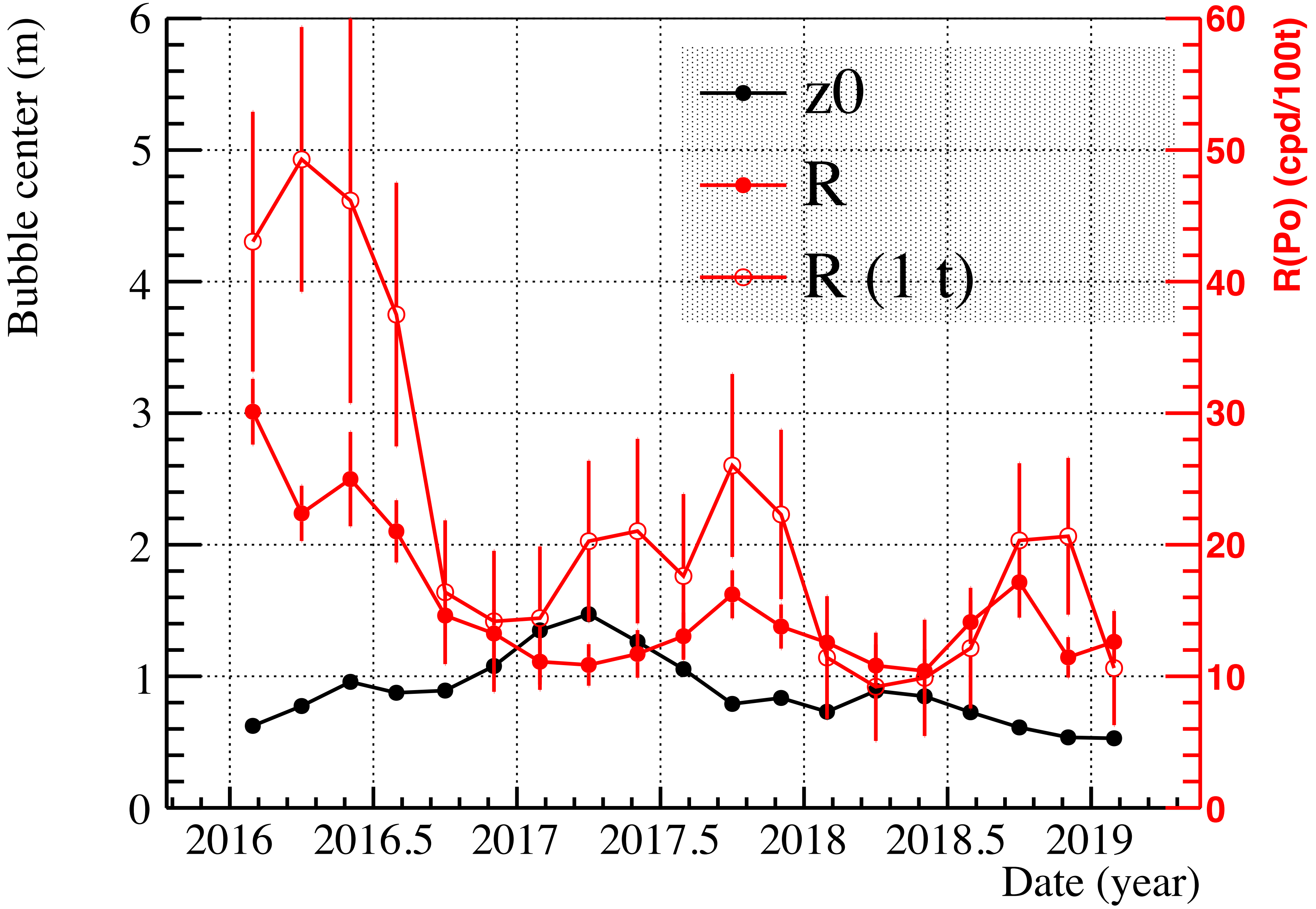


$$R(\rho^2, z) = N_0 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}$$

$\rho^2 = x^2 + y^2$

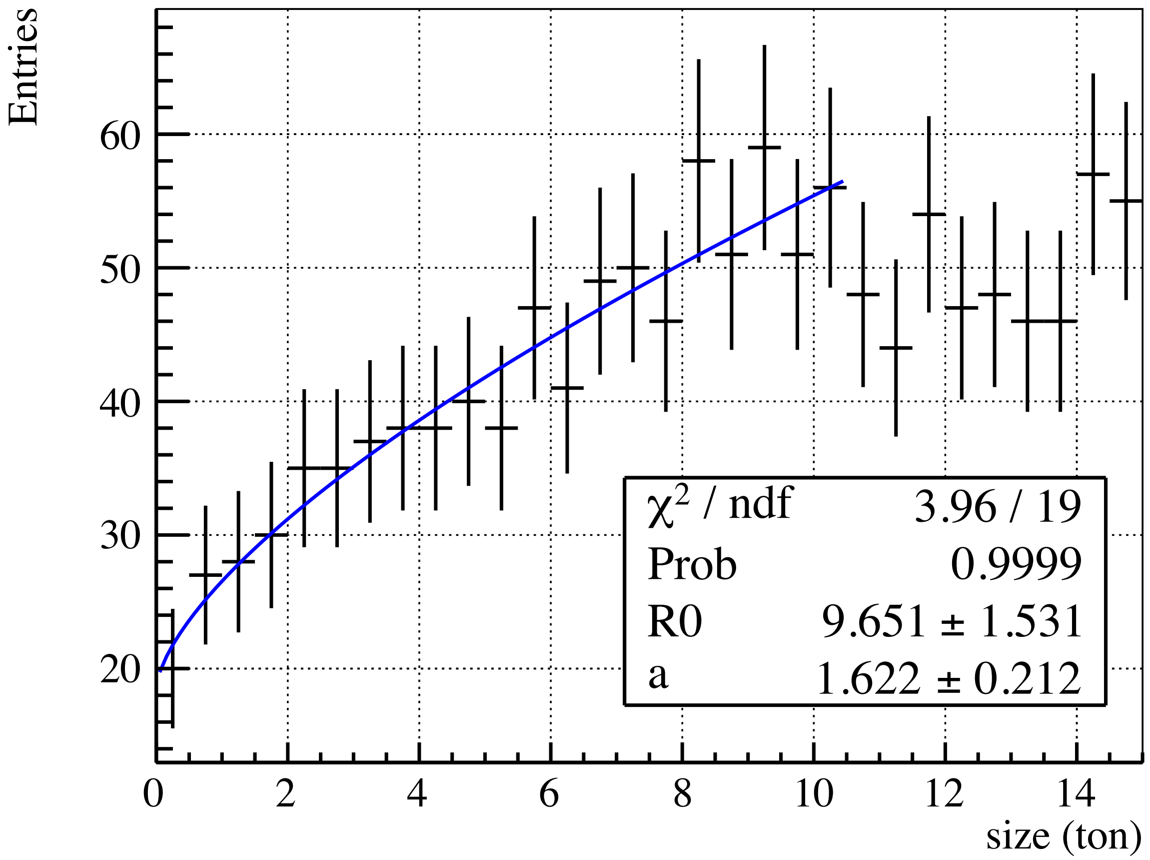
[ch 8] Get rid of migration ^{210}Po

- The minimum position is rather stable. not due to fluctuation.



[ch8] ^{210}Bi from ^{210}Po: vortex fit

- ^{210}Po from convection can be approximated with paraboloid function near the minimum.
- Rate @ minimum: supported ^{210}Po = ^{210}Bi



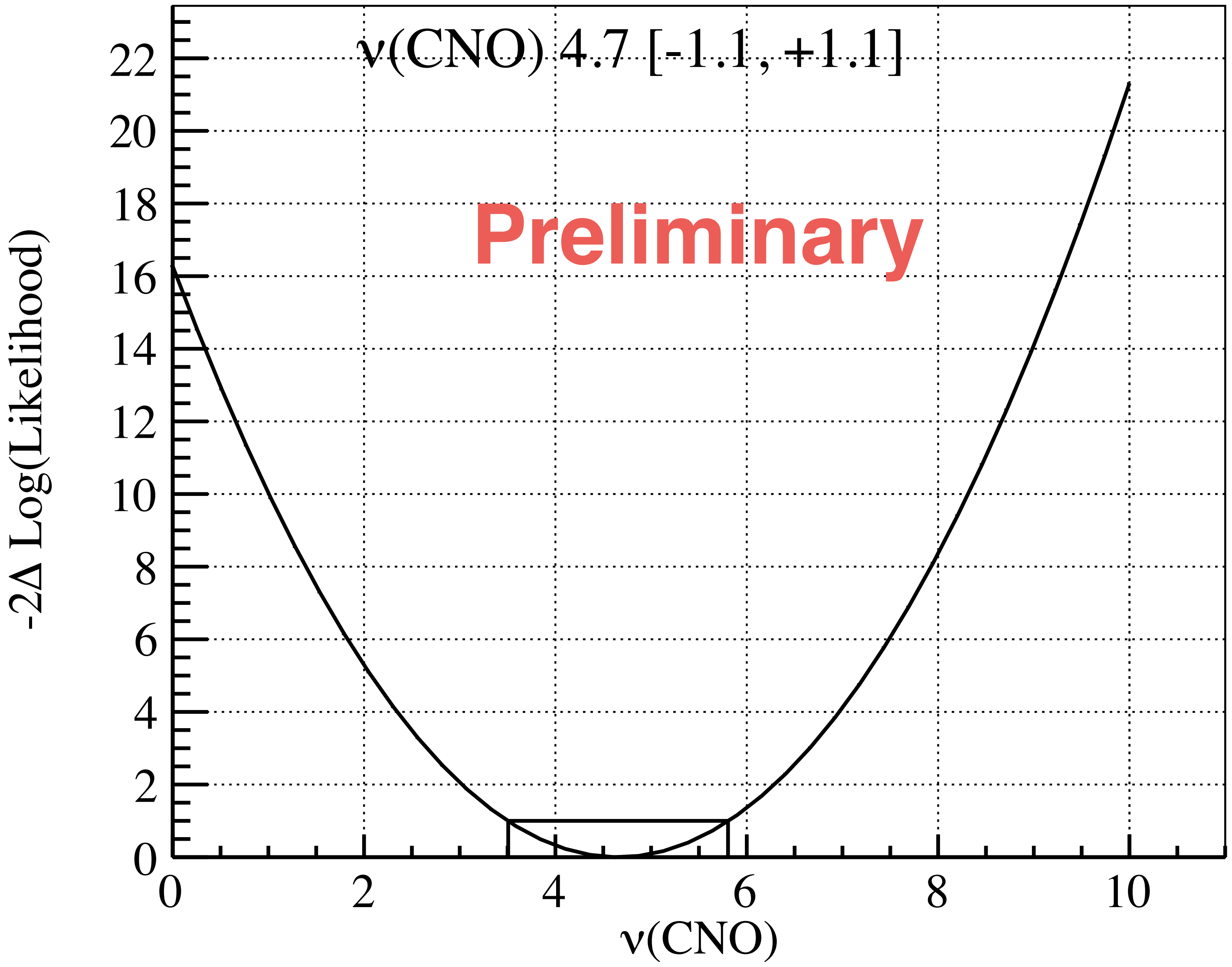
Define the iso-volume parameter ζ^3:

$$\zeta^3 = \left(\frac{x^2+y^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right)^{3/2},$$

$$9.65 \pm 1.62\,\mathrm{cpd}/100\mathrm{t}$$

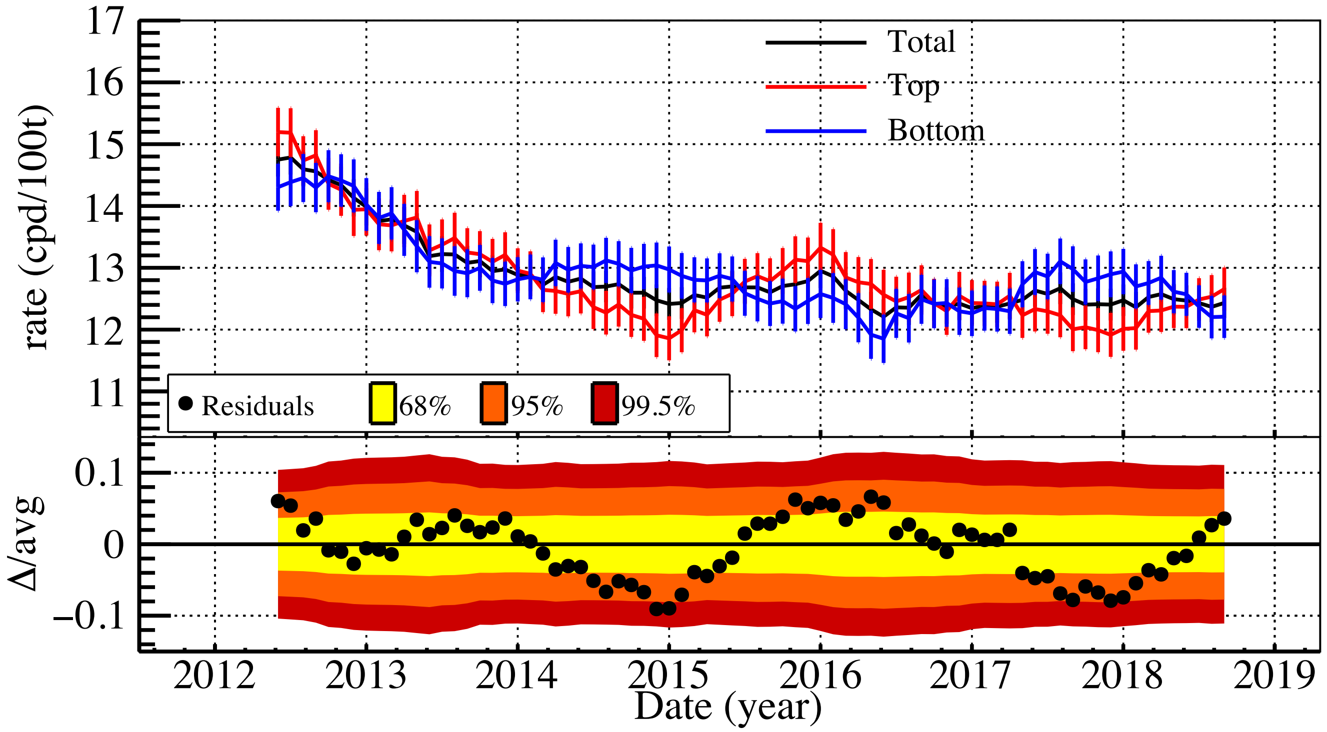
[ch8] CNO with ^{210}Bi constrained

- ^{210}Bi constrained. CNO: 4.7±1.1 cpd/100t.
- Next step: include systematic uncertainties (ongoing)

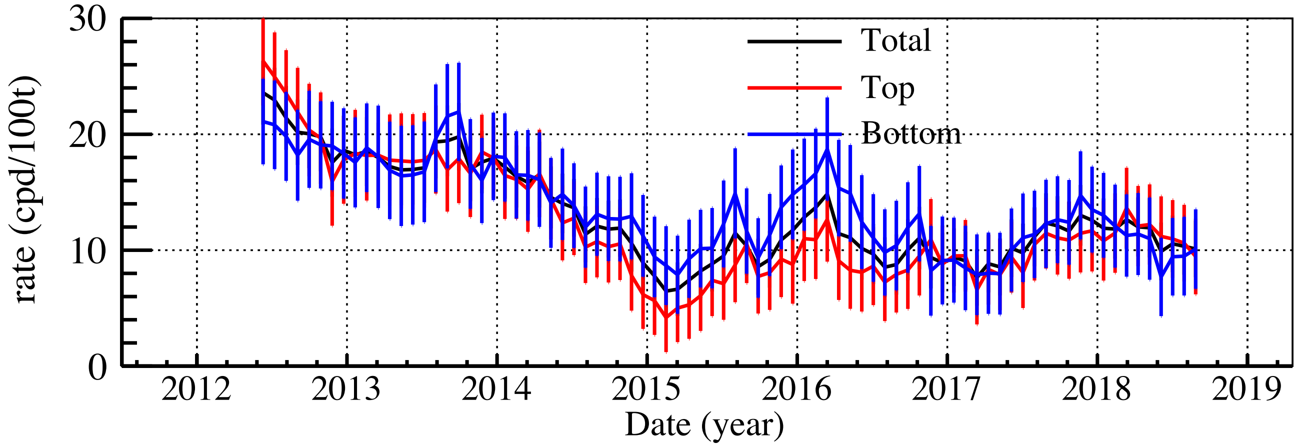


[ch8] CNO: systematics

Counting rate in FV(be7), Q_{geo} 284–471, no MLP



R(^{210}Bi) from fit. FV(pep), Q_{geo} 140-1500, comp fit

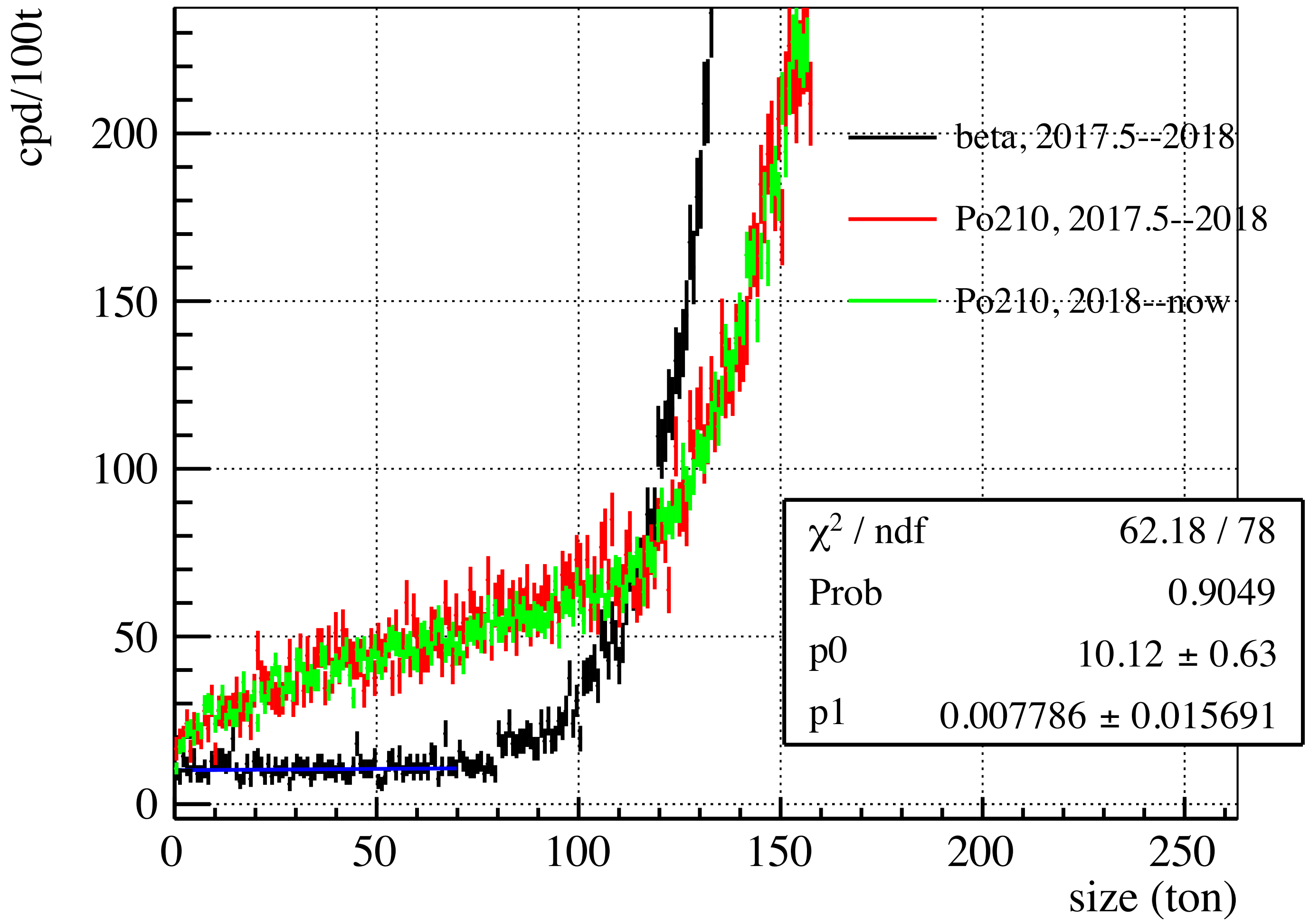


- (Top) ^{210}Bi rate from fit
- (Bottom) Number of events in an optimized energy rage
- Conclusion: ^{210}Bi rate is (almost) stable after ~2015

*bin space: 1 month. each bin correspond to 1 year data

[ch8] CNO: systematics

- The volume used to measure ^{210}Bi is smaller than the volume used to perform fit.
- Is ^{210}Bi uniform?

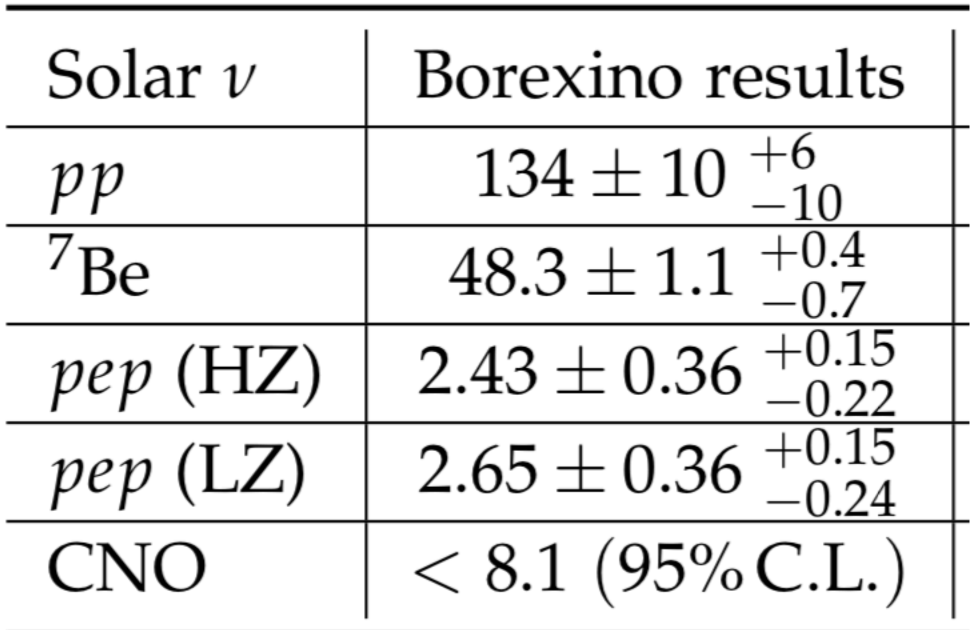


- clearly ^{210}Bi is uniform within certain range.
  - Δ=0.5±1.1 cpd/100t @ 70ton bubble

Summary of my contributions (CNO)

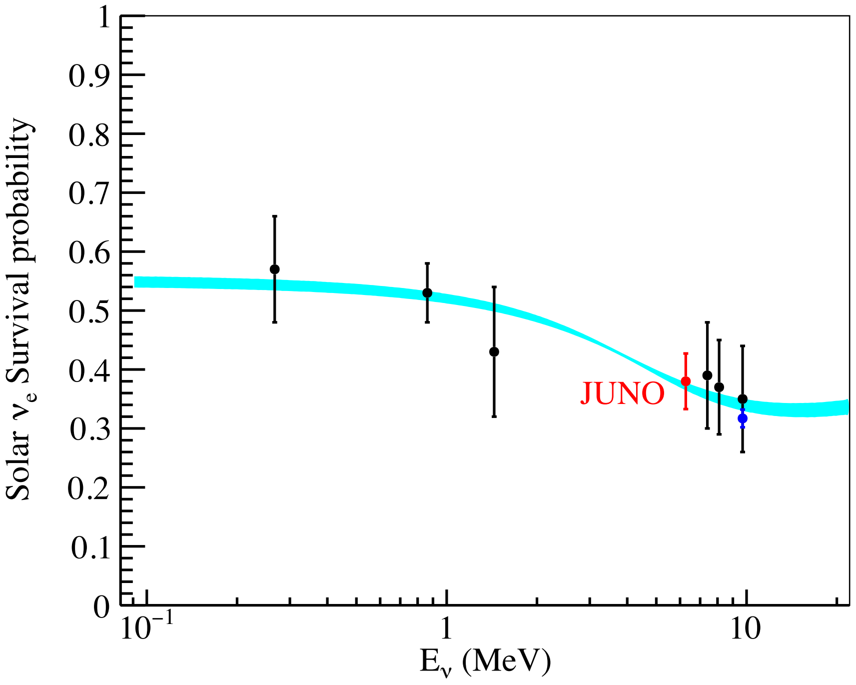
- Demonstrated ^{210}Bi uniformity and stability. Basic assumptions that our method is feasible.
- Breakthrough in determining the ^{210}Bi rate using ^{210}Po with “bubble/vortex” method.

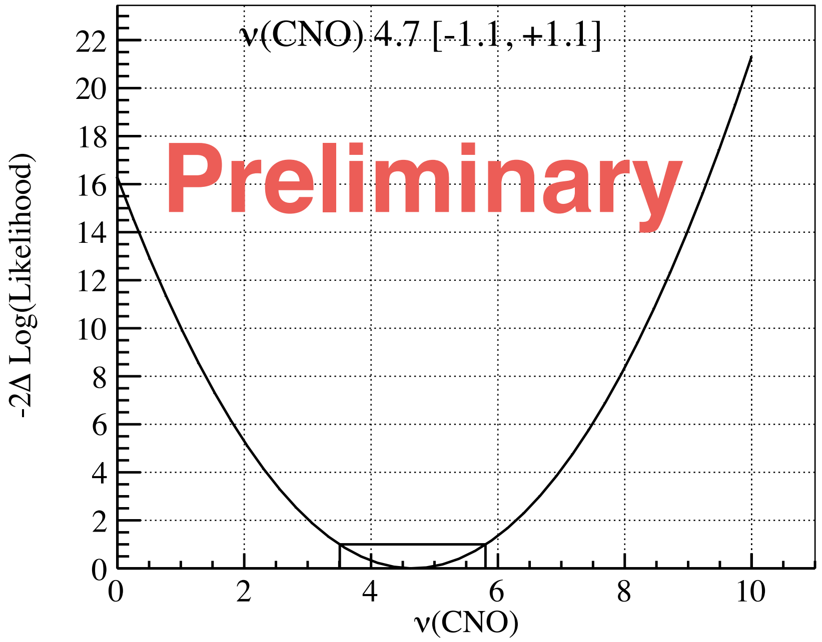
Conclusions

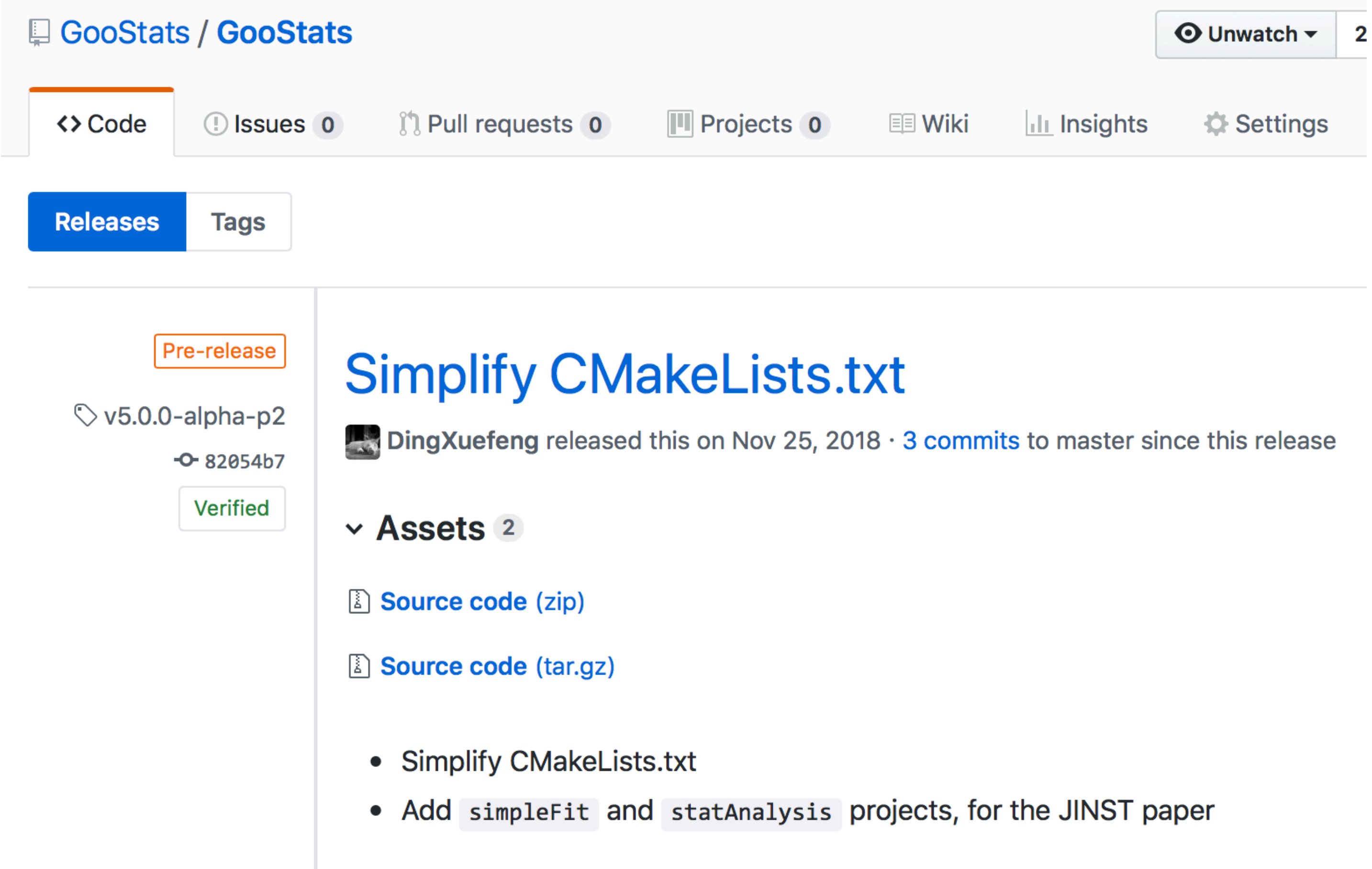


Solar ν	Borexino results
pp	$134 \pm 10 \, ^{+6}_{-10}$
^{7}Be	$48.3 \pm 1.1 \, ^{+0.4}_{-0.7}$
pep (HZ)	$2.43 \pm 0.36 \, ^{+0.15}_{-0.22}$
pep (LZ)	$2.65 \pm 0.36 \, ^{+0.15}_{-0.24}$
CNO	< 8.1 (95% C.L.)

M. Agostini et al., “**Comprehensive measurement of pp-chain solar neutrinos**,” *Nature*, vol. 562, no. 7728, pp. 505–510, Oct. 2018.







Simplify CMakeLists.txt

DingXuefeng released this on Nov 25, 2018 · 3 commits to master since this release

Assets 2

Source code (zip)

Source code (tar.gz)

- Simplify CMakeLists.txt
- Add `simpleFit` and `statAnalysis` projects, for the JINST paper

- Breakthrough that makes ana MV fit feasible: GPU fitter
- High precision measurement with Borexino
- 2 MeV ^{8}B solar neutrino detection with JUNO: door to MSW transition zone and new physics
- Breakthrough towards detection of CNO.

List of publications

8 conference talks (3 plenary talks); 26 papers

Selected main-contributor-papers (For my contributions please see *CV - selected papers*)

- Xuefeng Ding, **GooStats: A GPU-based framework for multi-variate analysis in particle physics**, *JINST* 13 (2018) no.12, P12018. DOI 10.1088/1748-0221/13/12/P12018, ARXIV: 1812.05686
- Borexino collaboration, **Comprehensive measurement of pp-chain solar neutrinos with Borexino**, *Nature*, vol. 562, no. 7728, pp. 505–510, 2018.
- Borexino collaboration, **Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data.** *Phys.Rev.D* 96 (2017) no.9, 091103 DOI: 10.1103/PhysRevD.96.091103, ARXIV: 1707.09355
- Daya Bay collaboration, **Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay** *Phys.Rev.Lett*. 116 (2016) no.6, 061801, Erratum: *Phys.Rev.Lett*. 118 (2017) no.9, 099902 DOI: 10.1103/PhysRevLett.116.061801, ARXIV: 1508.04233
- X. F. Ding *et al.*, **Measurement of the fluorescence quantum yield of bis-MSB** *Chin.Phys.C* 39 (2015) no.12, 126001 DOI: 10.1088/1674-1137/39/12/126001, ARXIV: 1506.00240

Invited Conference Talks

- **Prospects of neutrino mass ordering and solar neutrinos with JUNO.** *Louise Lake Winter Institute.* 2019 August 10-16. Fairmont Chateau. Edmonton, Alberta, Canada (Plenary)
- **Status and Physics of JUNO.** *The 20th International Workshop on Neutrinos from Accelerators.* 2018 August 12-18. Virginia Tech. Blacksburg, VA, U.S. (Plenary)
- **Latest Phase-II results and Prospects of CNO neutrino detection with Borexino.** *International Symposium of Neutrino Frontier.* 2018 July 16-19. ICISE center, Quy Nhon, Vietnam. (Plenary)

Full list of published papers

1. P. Lombardi *et al.*, **Distillation and stripping pilot plants for the JUNO neutrino detector: Design, operations and reliability**, *Nucl.Instrum.Meth. A* 925 (2019) 6-17 DOI 10.1016/j.nima.2019.01.071, ARXIV: 1902.05288
2. Xuefeng Ding, **GooStats: A GPU-based framework for multi-variate analysis in particle physics**, *JINST* 13 (2018) no.12, P12018. DOI 10.1088/1748-0221/13/12/P12018, ARXIV: 1812.05686
3. A. Porcelli *et al.*, **Recent Borexino results and perspectives of the SOX measurement**, *EPJ Web Conf.,* 182 (2018) 02099. DOI 10.1051/epjconf/201818202099
4. Lino Miramonti *et al.*, **Solar Neutrinos Spectroscopy with Borexino Phase-II**, *Universe,* 4 (2018) no. 11, 118. DOI 10.3390/universe4110118
5. Borexino collaboration, **Comprehensive measurement of pp-chain solar neutrinos with Borexino**, *Nature*, vol. 562, no. 7728, pp. 505–510, 2018.
6. Qin Liu, *et al.*, **A vertex reconstruction algorithm in the central detector of JUNO.** *JINST* 13 (2018) no.9, T09005 DOI: 10.1088/1748-0221/13/09/T09005, ARXIV: 1803.09394
7. M. Grassi *et al.* **Charge reconstruction in large-area photomultipliers,** *JINST*, 13 (2018) no.02, P02008, DOI: 10.1088/1748-0221/13/02/P02008, ARXIV: 1801.08690
8. M. Gromov *et al.* **CeSOX: An experimental test of the sterile neutrino hypothesis with Borexino** *J.Phys.Conf.Ser.* 934 (2017) no.1, 012003, DOI: 10.1088/1742-6596/934/1/012003
9. Lea Di Noto *et al.* **The SOX experiment hunts the sterile neutrino** *Pos NEUTEL2017*(2018) 043, DOI: 10.22323/1.307.0043
10. Borexino collaboration, **Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data.** *Phys.Rev.D* 96 (2017) no.9, 091103 DOI: 10.1103/PhysRevD.96.091103, ARXIV: 1707.09355
11. Borexino collaboration, **A Search for Low-energy Neutrinos Correlated with Gravitational Wave Events GW 150914, GW 151226, and GW 170104 with the Borexino Detector** *Astrophys.J.* 850 (2017) no.1, 21 DOI: 10.3847/1538-4357/aa9521, ARXIV: 1706.10176
12. Borexino collaboration, **The Monte Carlo simulation of the Borexino detector**, *Astropart.Phys.* 97 (2018) 136-159 DOI: 10.1016/j.astropartphys.2017.10.003, ARXIV: 1704.02291
13. Borexino collaboration, **Seasonal Modulation of the ^{7}Be Solar Neutrino Rate in Borexino** *Astropart.Phys.* 92 (2017) 21-29 DOI: 10.1016/j.astropartphys.2017.04.004, ARXIV: 1701.07970
14. B. Caccianiga, *et al.*, **Short distance neutrino Oscillations with BoreXino: SOX** *Nuovo Cim.* 40 (2017) no.5, 162 DOI: 10.22323/1.307.0043
15. Daya Bay collaboration, **Measurement of electron antineutrino oscillation based on 1230 days of operation of the Daya Bay experiment** *Phys.Rev. D.* 95 (2017) no.7, 072006 DOI: 10.1103/PhysRevD.95.072006 ARXIV: 1610.04802
16. Daya Bay collaboration, **Study of the wave packet treatment of neutrino oscillation at Daya Bay** *Eur.Phys.J.C,* 77 (2017) no.9, 606 DOI: 10.1140/epjc/s10052-017-4970-y, ARXIV: 1608.01661
17. Daya Bay collaboration, **Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay** *Chin.Phys. C.* 41 (2017) no.1, 013002 DOI: 10.1088/1674-1137/41/1/013002 ARXIV: 1607.05378
18. Daya Bay and MINOS collaboration, **Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments** *Phys.Rev.Lett.* 117 (2016) no.15, 151801, Addendum: *Phys.Rev.Lett.* 117 (2016) no.20, 209901 DOI: 10.1103/PhysRevLett.117.151801, ARXIV: 1607.01177
19. Daya Bay collaboration, **Improved Search for a Light Sterile Neutrino with the Full Configuration of the Daya Bay Experiment** *Phys.Rev.Lett.* 117 (2016) no.15, 151802 DOI: 10.1103/PhysRevLett.117.151802 ARXIV: 1607.01174
20. Daya Bay collaboration, **New measurement of θ_{13} via neutron capture on hydrogen at Daya Bay** *Phys.Rev.D* 93 (2016) no.7, 072011 DOI: 10.1103/PhysRevD.93.072011, ARXIV: 1603.03549
21. Daya Bay collaboration, **Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay** *Phys.Rev.Lett*. 116 (2016) no.6, 061801, Erratum: *Phys.Rev.Lett*. 118 (2017) no.9, 099902 DOI: 10.1103/PhysRevLett.116.061801, ARXIV: 1508.04233
22. Daya Bay collaboration, **The Detector System of The Daya Bay Reactor Neutrino Experiment** *Nucl.Instrum.Meth.A* 811 (2016) 133-161 DOI: 10.1016/j.nima.2015.11.144, ARXIV: 1508.03943
23. X. F. Ding *et al.*, **Measurement of the fluorescence quantum yield of bis-MSB** *Chin.Phys.C* 39 (2015) no.12, 126001 DOI: 10.1088/1674-1137/39/12/126001, ARXIV: 1506.00240
24. X. C. Ye, *et al.,* **Preliminary study of light yield dependence on LAB liquid scintillator composition** *Chin.Phys.C* 39 (2015) no.9, 096003 DOI: 10.1088/1674-1137/39/9/096003, ARXIV: 1506.00237
25. Daya Bay collaboration, **New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay** *Phys.Rev.Lett*. 115 (2015) no.11, 111802 DOI: 10.1103/PhysRevLett.115.111802, ARXIV: 1505.03456
26. D. M. Xiao *et al.*, **Temperature dependence of the light yield of the LAB-based and mesitylene-based liquid scintillators** *Chin.Phys.C* 38 (2014) no.11, 116001 DOI: 10.1088/1674-1137/38/11/116001 ARXIV: 1402.6871

Note on arXiv

- Lino Miramonti *et al.*, **Recent results on pp-chain solar neutrinos with the Borexino detector**, ARXIV: 1901.09965
- M. Reguzzoni *et al.*, **GIGJ: a crustal gravity model of the Guangdong Province for predicting the geoneutrino signal at the JUNO experiment**, ARXIV: 1901.01945
- A. Pocar *et al.* **Solar Neutrino Physics with Borexino,** *XXXVIII International Symposium on Physics in Collision,* ARXIV: 1812.02326
- A. Pocar *et al.* **Solar Neutrino Physics with Borexino,** *15th International Conference on Topics in Astroparticle and Underground Physics,* ARXIV: 1810.12967
- Borexino collaboration **Modulations of the Cosmic Muon Signal in Ten Years of Borexino Data,** ARXIV: 1801.08690
- X. F. Ding *et al.*, **Speeding up complex multivariate data analysis in Borexino with parallel computing based on Graphics Processing Unit,** *15th International Conference on Topics in Astroparticle and Underground Physics,* ARXIV: 1805.11125
- W. T. Luo *et al.* **Quenching of fluorescence for linear alkylbenzene,** ARXIV: 1801.04432
- JUNO collaboration, **JUNO Conceptual Design Report,** ARXIV: 1508.07166

More Conference talks

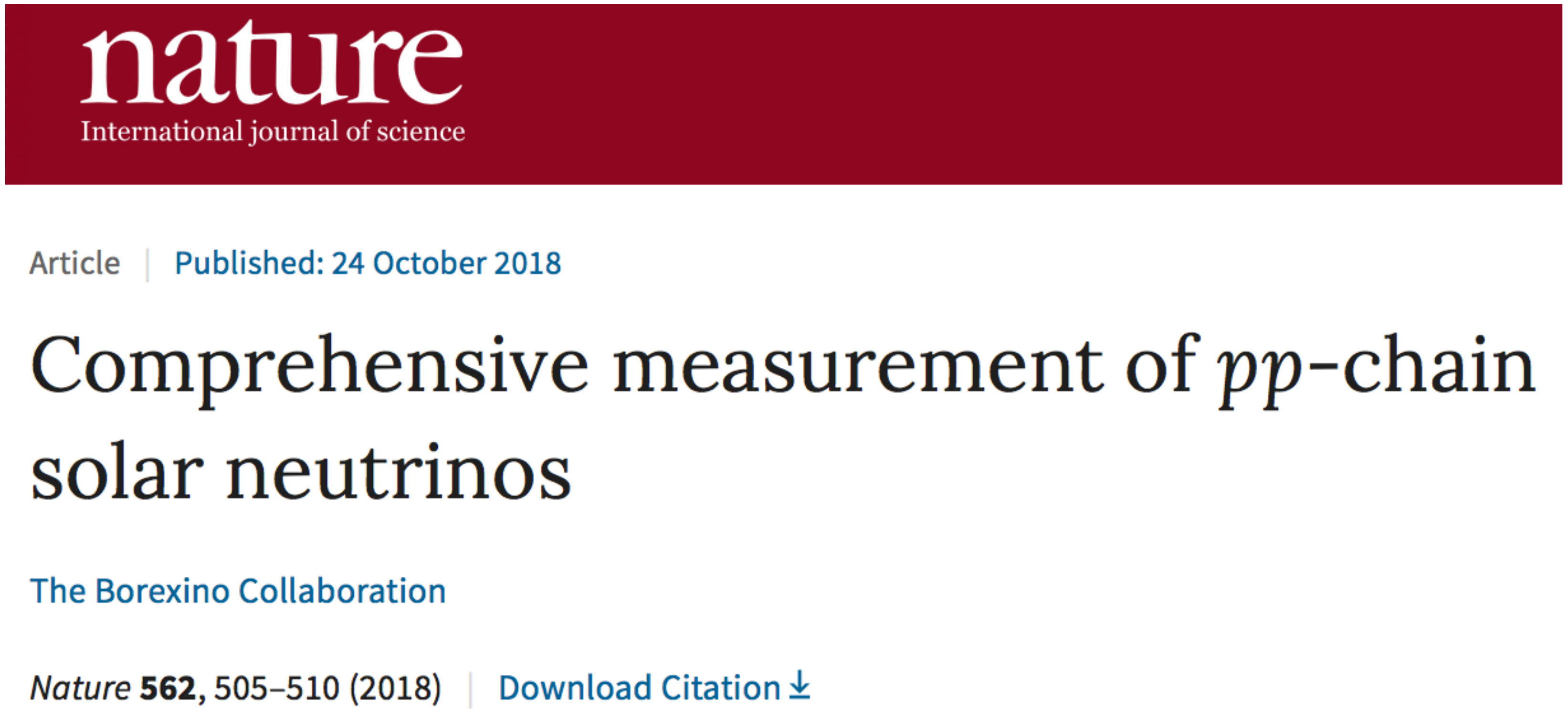
- **A GPU-based framework for multi-variate analysis in particle physics**. PHYSTAT-nu. 2019 January 21-26. CERN
- **Probing Neutrino Mass Ordering and Solar neutrinos with JUNO detector**. The 20th International Workshop on Neutrinos from Accelerators. 2018 August 12-18. Virginia Tech. Blacksburg, VA, U.S.
- **Effects influencing the energy non linearity of liquid scintillators and their compensation**. *Energy Scale Calibration in Antineutrino Precision Experiments 2018.* 2018 June 1-2. MPI für Kernphysik. Heidelberg, Germany. (Invited)
- **Impact of the Rayleigh scattering on the energy resolution of JUNO detector**. *Software and analysis in particle physics*. Weihai, China 2013

Posters

- **Clusterization algorithm for sub-MeV events reconstruction in JUNO**, *Neutrino 2018*, 2018, Heidelberg
- **Speed up complex multivariate analysis in Borexino analysis with parallel computing based on Graphics Processing Unit**, XXVIII International Symposium on Lepton Photon Interactions at High Energies, 2017, GuangZhou
- **Borexino Phase-II solar neutrino results**, XXVIII International Symposium on Lepton Photon Interactions at High Energies, 2017, GuangZhou
- **Speed up complex multivariate analysis in Borexino analysis with parallel computing based on Graphics Processing Unit**, XV International Conference on Topics in Astroparticle and Underground Physics, 2017, Sudbury
- **Measurement of fluorescence quantum efficiency of bisMSB and PPO**, *Neutrino 2016*, 2016, London

Related publications

- The results of this work has been used in Nature paper.
- A new paper with more details has been submitted to PRD (1707.09279)



nature
International journal of science

Article | Published: 24 October 2018

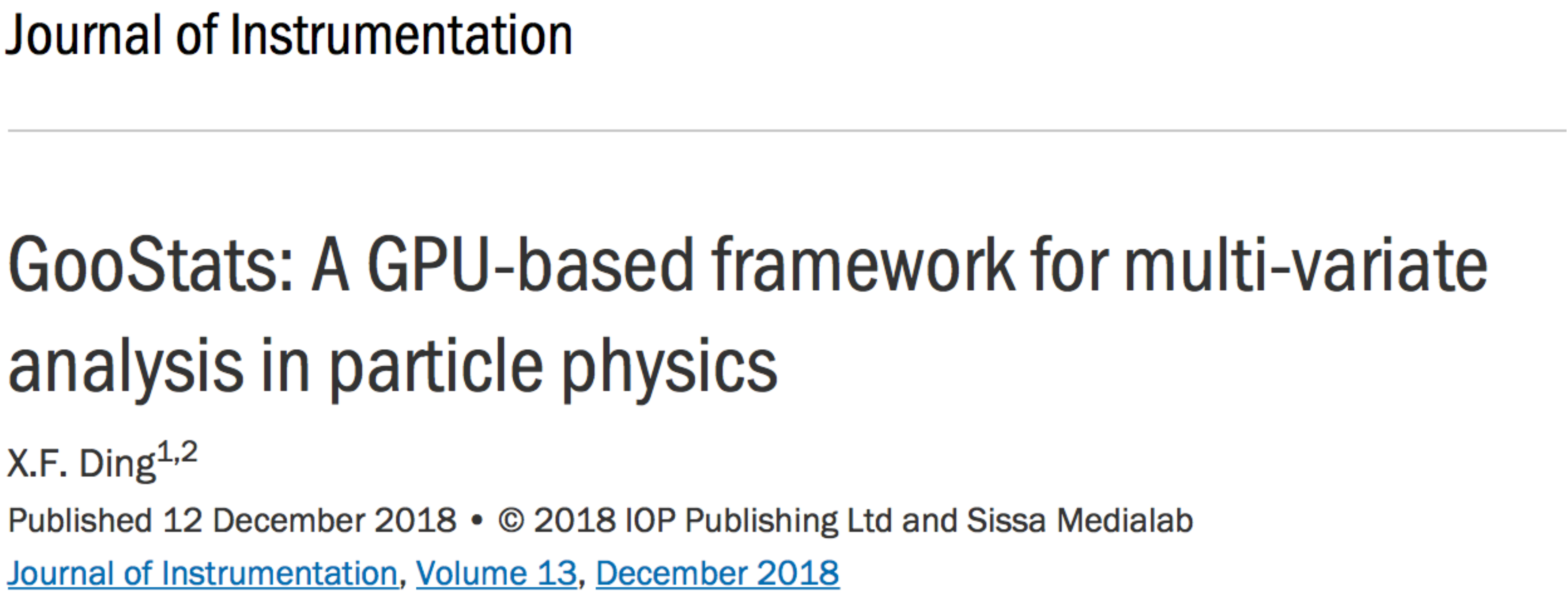
Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration

Nature **562**, 505–510 (2018) | Download Citation ⤓

- The parallel computing tool has been reported in

open source proj.: github.com/GooStats/GooStats



Journal of Instrumentation

GooStats: A GPU-based framework for multi-variate analysis in particle physics

X.F. Ding[1,2]

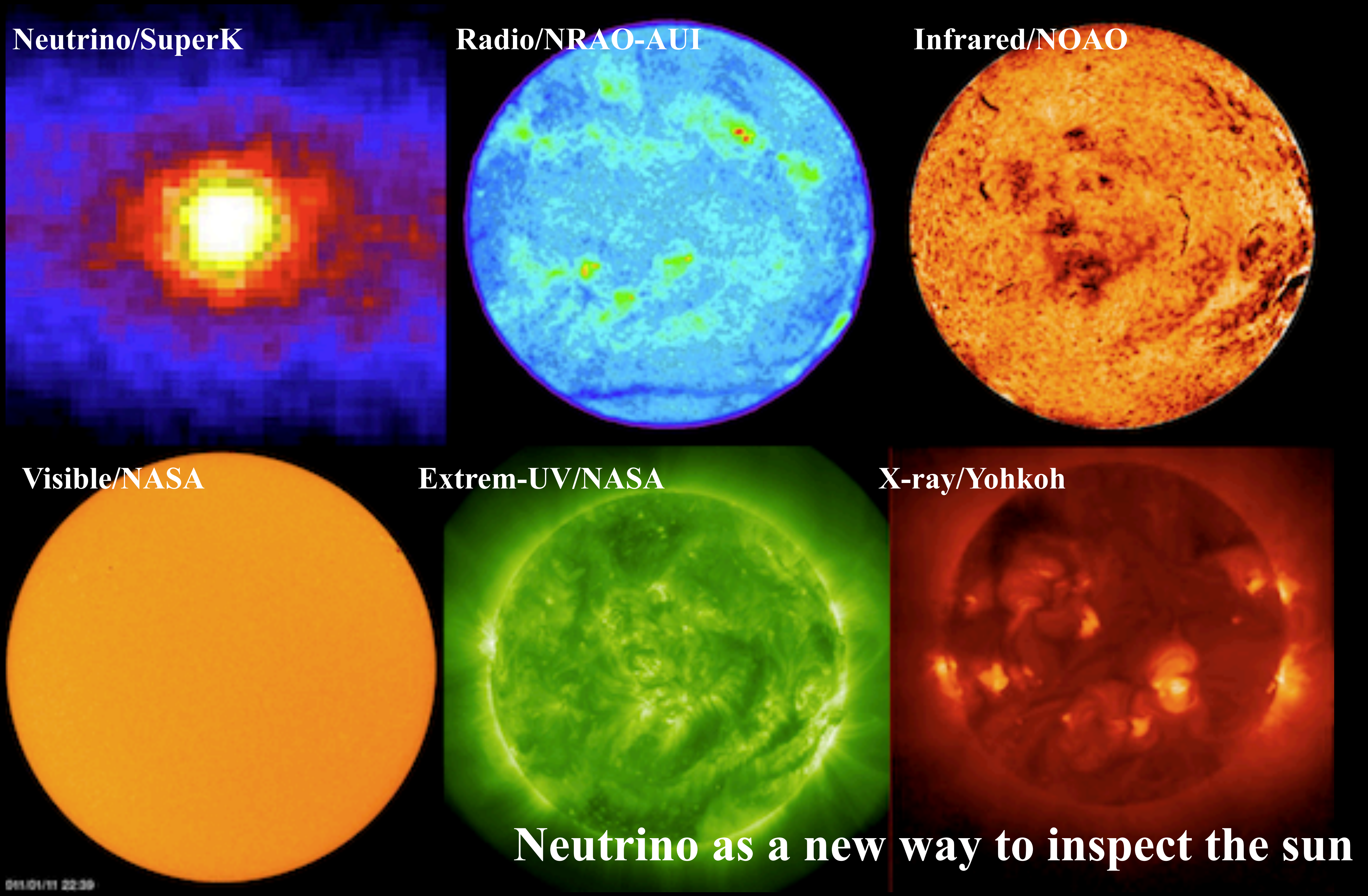
Published 12 December 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab

Journal of Instrumentation, Volume 13, December 2018

Thanks

Dusk of L'Aquila

Backup

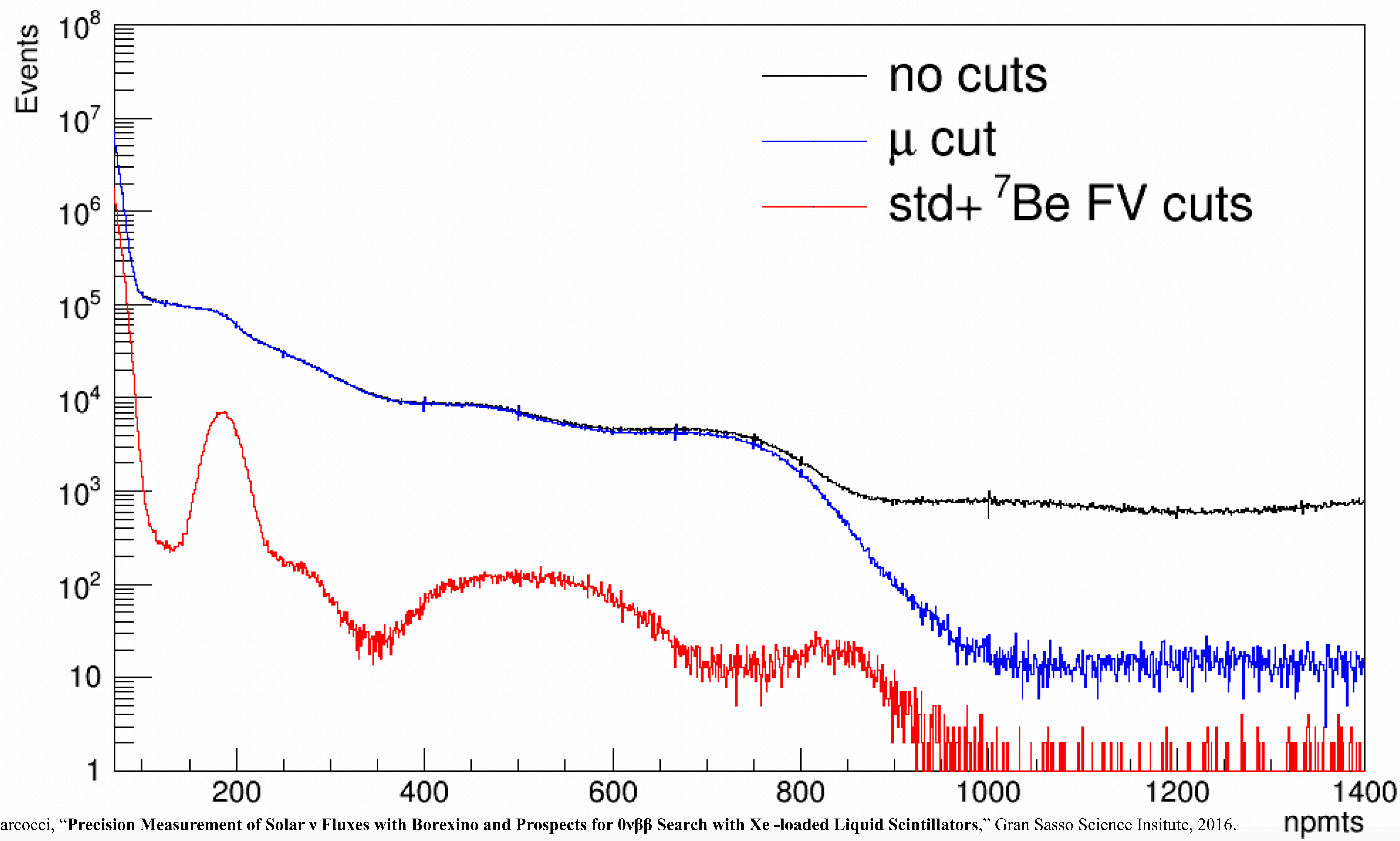


Neutrino as a new way to inspect the sun

Images of the Sun: whereas the neutrino emission originates in the dense core of the Sun, photonic observations originate in the solar surface and atmosphere. From top left: Neutrino ‘image’ of the Solar core (Image credit: R. Svoboda, K. Gordan, LSU), radio emission from the solar atmosphere (Image credit: S. White, University of Maryland, NRAO/AUI), infrared image from the solar chromosphere (Image credit: National Solar Observatory, Kitt Peak/NOAO), visible image of the solar surface (Image credit: SOHO/ESA/NASA), extreme ultraviolet emission from the corona (Image credit: NASA/SDO/AIA), X-ray emission from the solar corona (Image credit: Yohkoh).

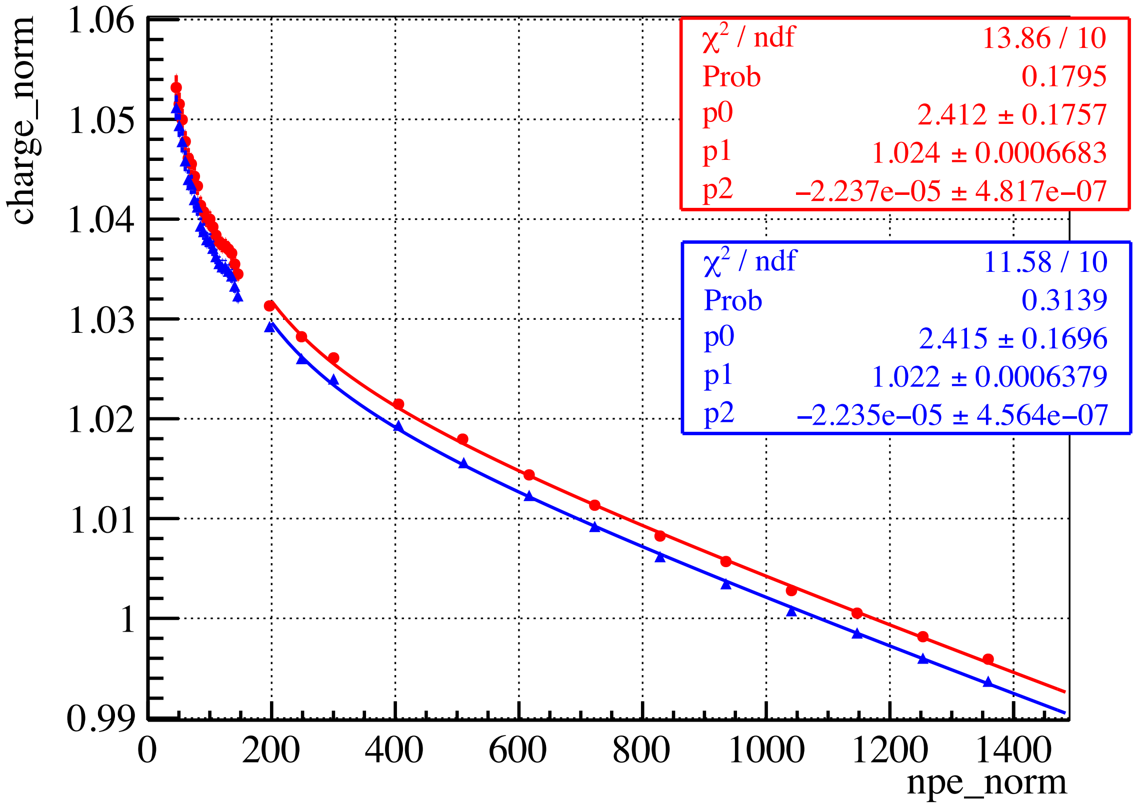
Event selection

- Reject cosmogenic isotope decay, γs from outside and noise



S. Marcocci, "**Precision Measurement of Solar ν Fluxes with Borexino and Prospects for 0νββ Search with Xe -loaded Liquid Scintillators**," Gran Sasso Science Insitute, 2016.

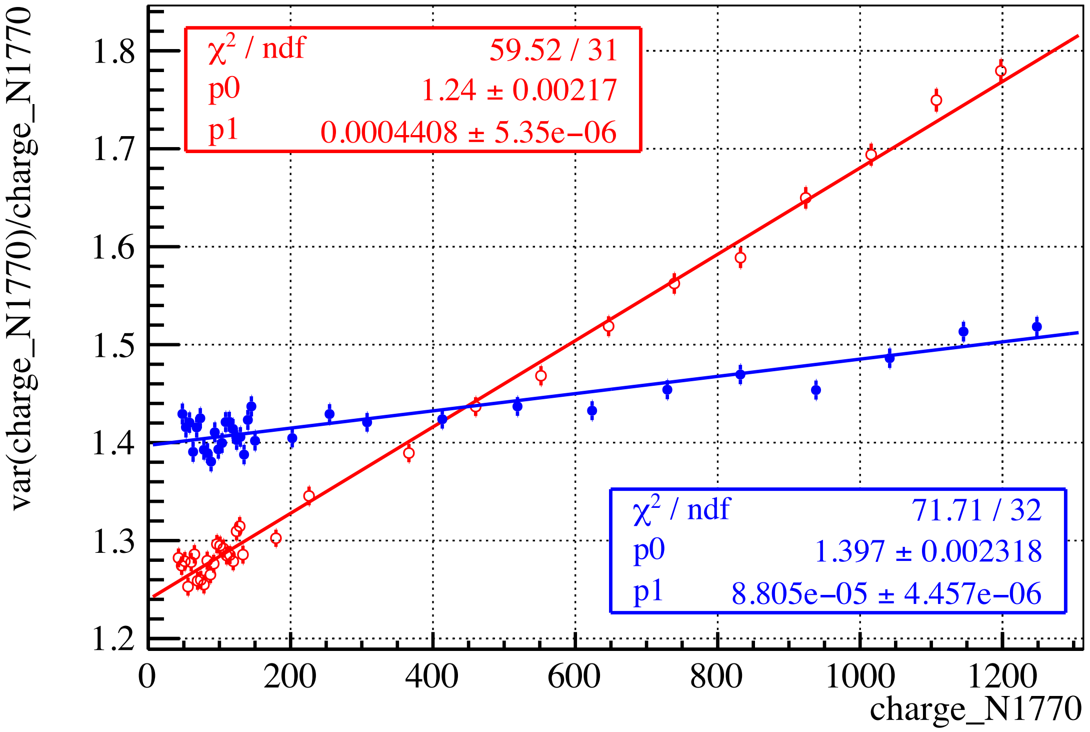
[ch4] charge RPF (sum of charge)



Average

$$\mu_{\text{p.e.}} = \varepsilon(\mathbf{r}) \cdot Y_{\text{p.e.}} \cdot \left(f_{\text{qch.}}(E) + \mu_{L_{\text{Cher.}}}(E) \cdot \text{fCher}\right)$$

$$\mu^{\text{FV}}_{\text{n.Q}} = p_{\text{dn}} + (1+p_{\text{mis.}}) \cdot \mu_{\text{n.p.e.}} + p_{\text{quadr.}} \left(\mu_{\text{n.p.e.}}\right)^2$$

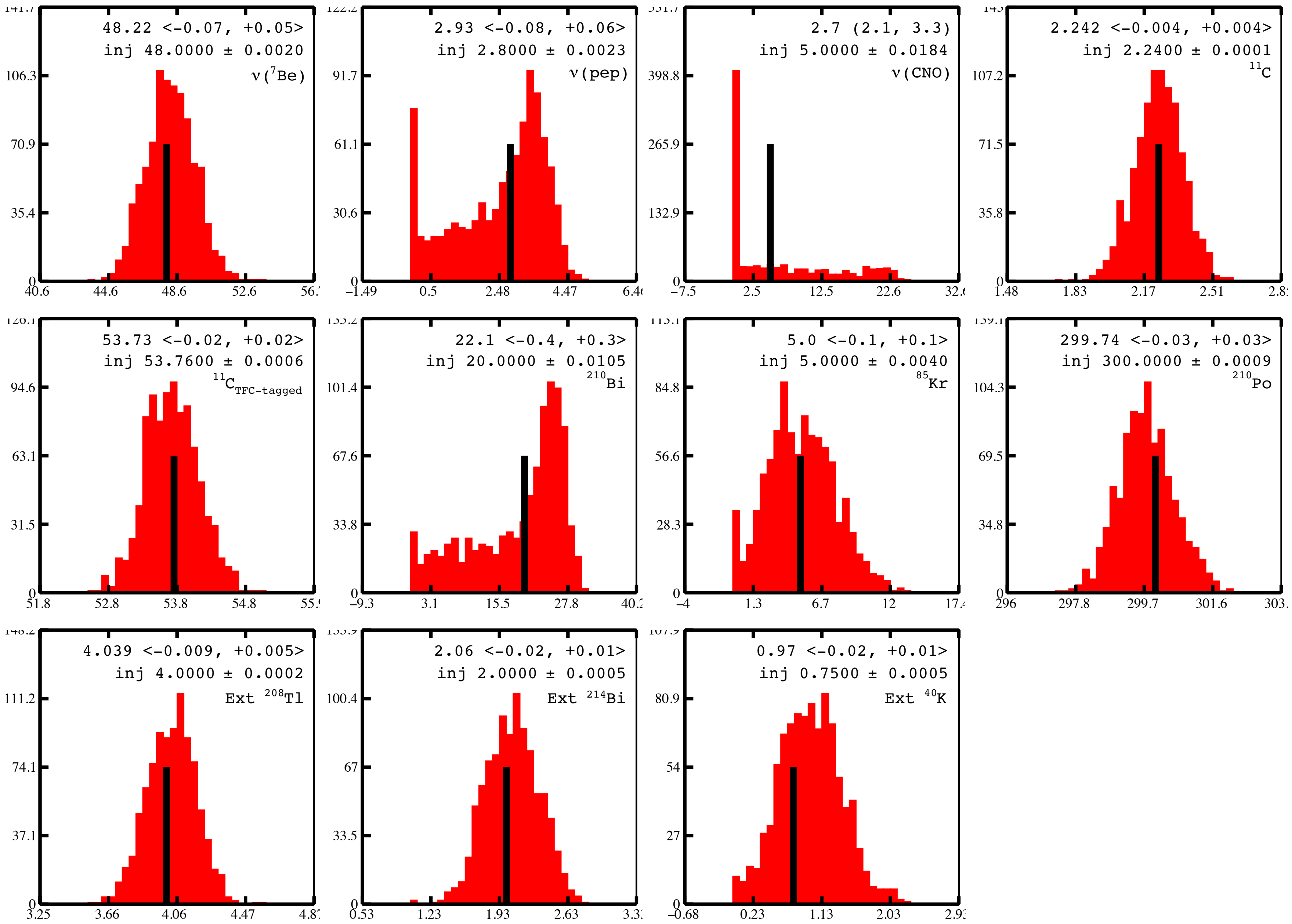


Variance

$$\text{Var}(N^{\text{FV}}_{\text{n.Q}}) = f^{Q}_{\text{eq.}} \cdot (1+v_1) \cdot \mu^{\text{FV}}_{\text{n.Q}} + \sigma_T^2 \cdot \left(\mu^{\text{FV}}_{\text{n.Q}}\right)^2$$

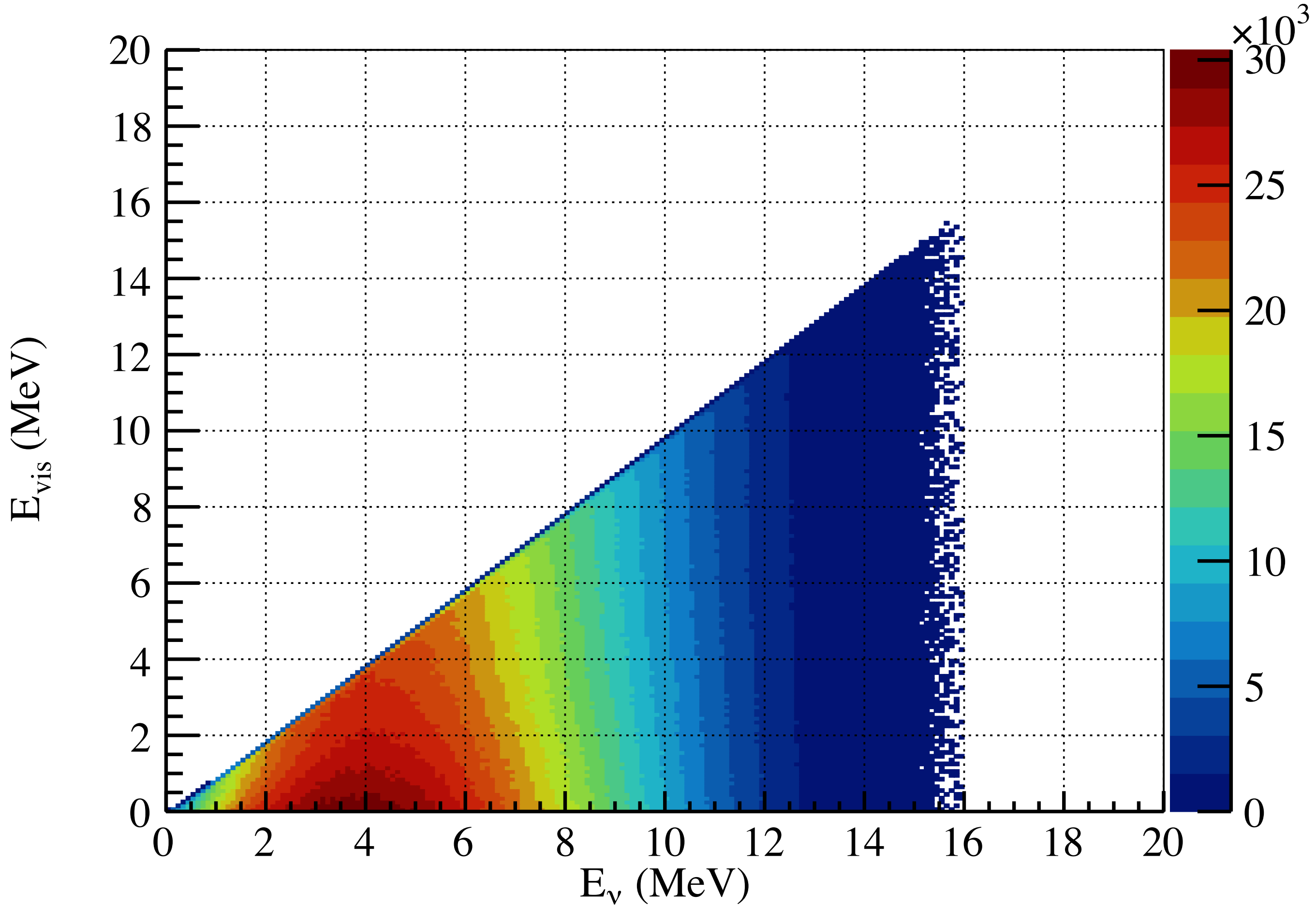
Validation: charge (sum of charge)

- Produce pseudo-experiment spectra with full MC simulation.
- Fit with analytical functions and compare fit results with inj.

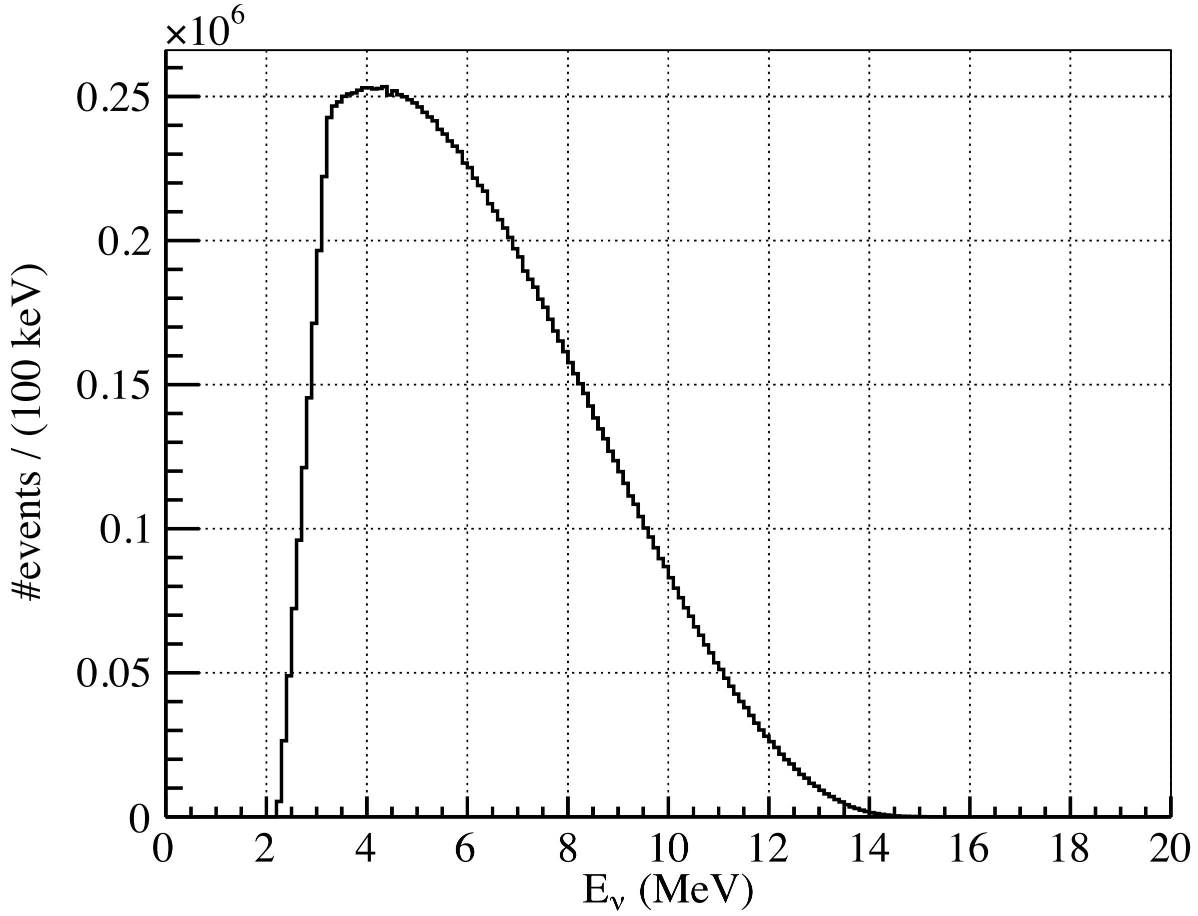


Average ν_e Energy

- ROI: Kinetic energy of electron ***T*** ~ [2, 3] MeV
- Average energy of contribution neutrinos: **6.18 MeV**



E_ν-T matrix

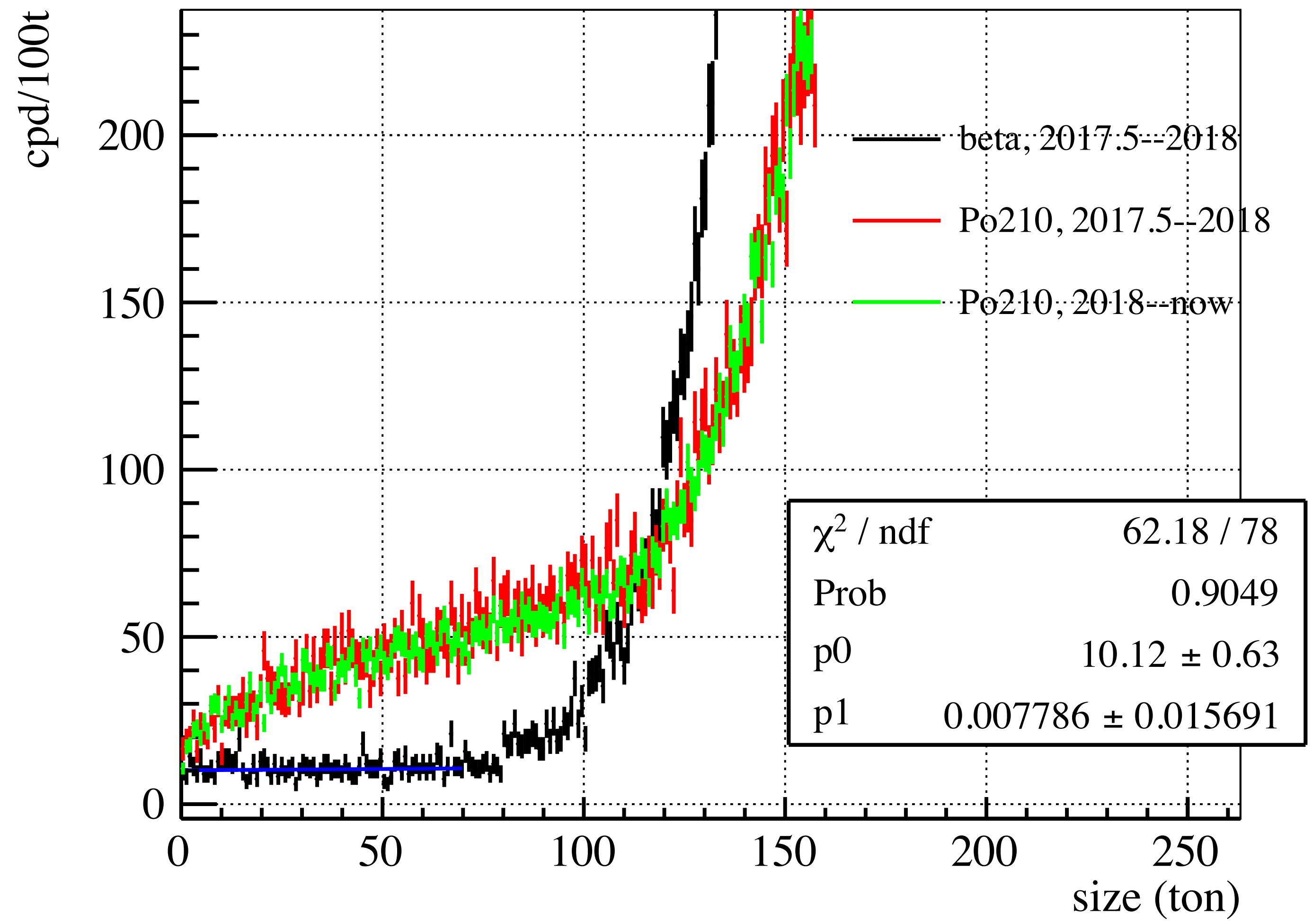


E_ν ~T in [2, 3] MeV

[ch 8] Get rid of migration ^{210}Po

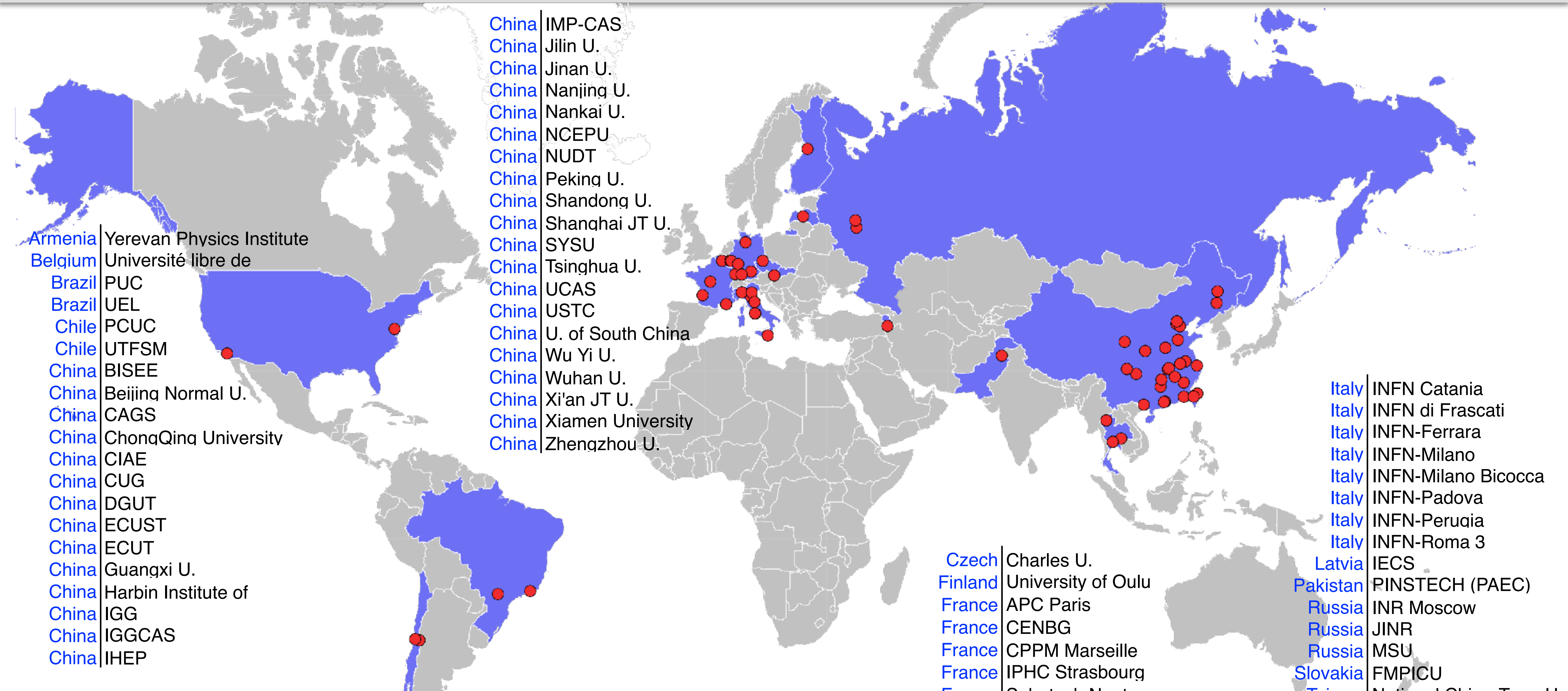
Define the iso-volume parameter ζ^3:

$$\zeta^3 = \left(\frac{x^2 + y^2}{a^2} + \frac{(z - z_0)^2}{b^2} \right)^{3/2},$$



- This plot shows good uniformity of beta events
  - Δ=0.5±1.1 cpd/100t @ 70ton bubble
- Macroscopic ^{210}Po trend is similar in different periods

JUNO collaboration



Armenia	Yerevan Physics Institute
Belgium	Université libre de
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
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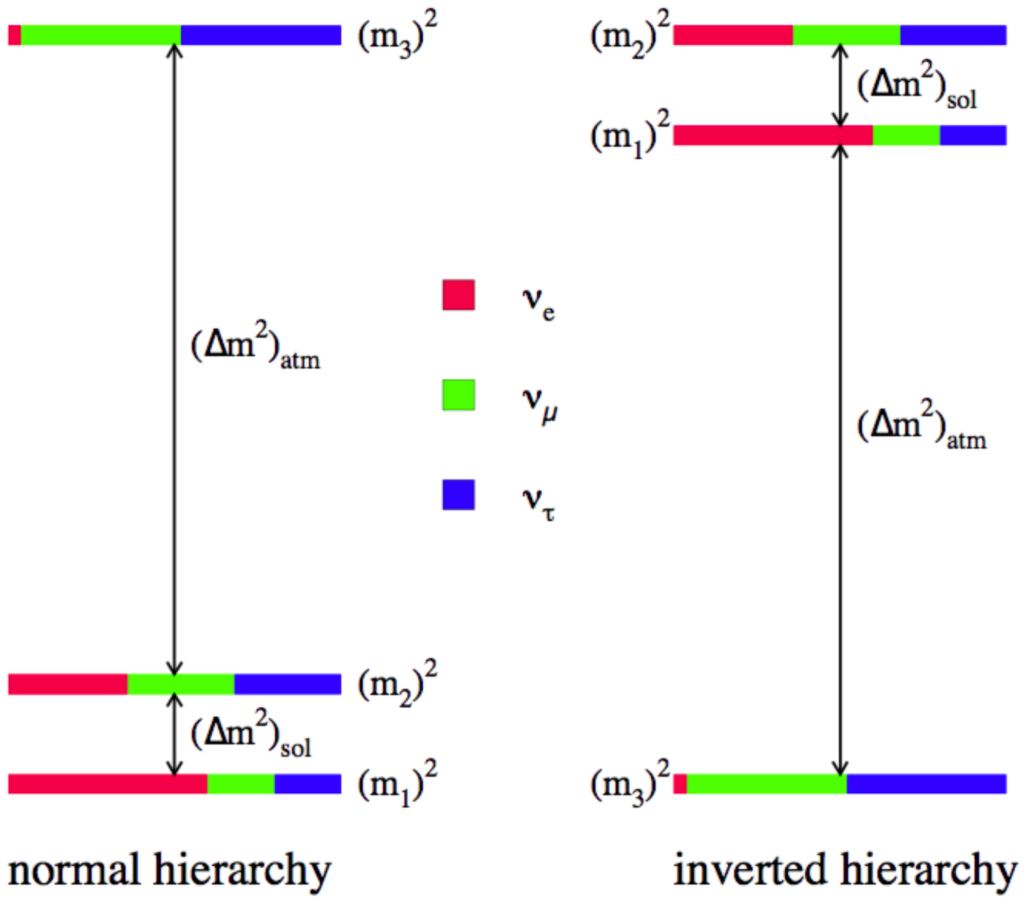
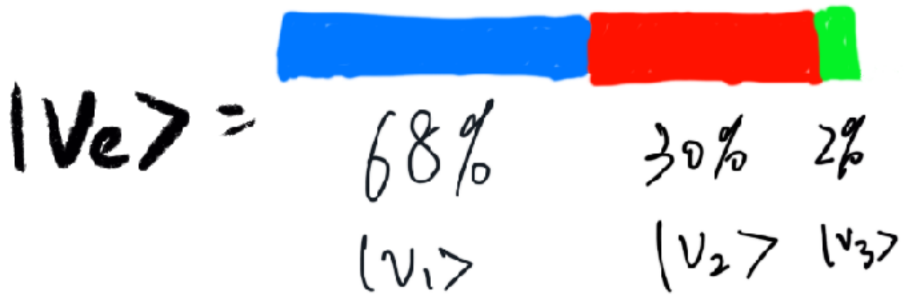
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

Collaboration established on July 2014

Now 77 institutions ~600 collaborators

Main goal: neutrino mass ordering





- ν_1, ν_2, ν_3 defined according to fraction in ν_e
- ν_2 is heavier than ν_1 (sun+MSW)
- we don't know if ν_3 is heavier (Normal ordering, NO) or lighter (Inverted ordering, IO) than ν_2

NMO

neutrino mass ordering

See F. An, et al., "Neutrino physics with JUNO," J. Phys. G Nucl. Part. Phys., vol. 43, no. 3, p. 030401, 2016. page 22

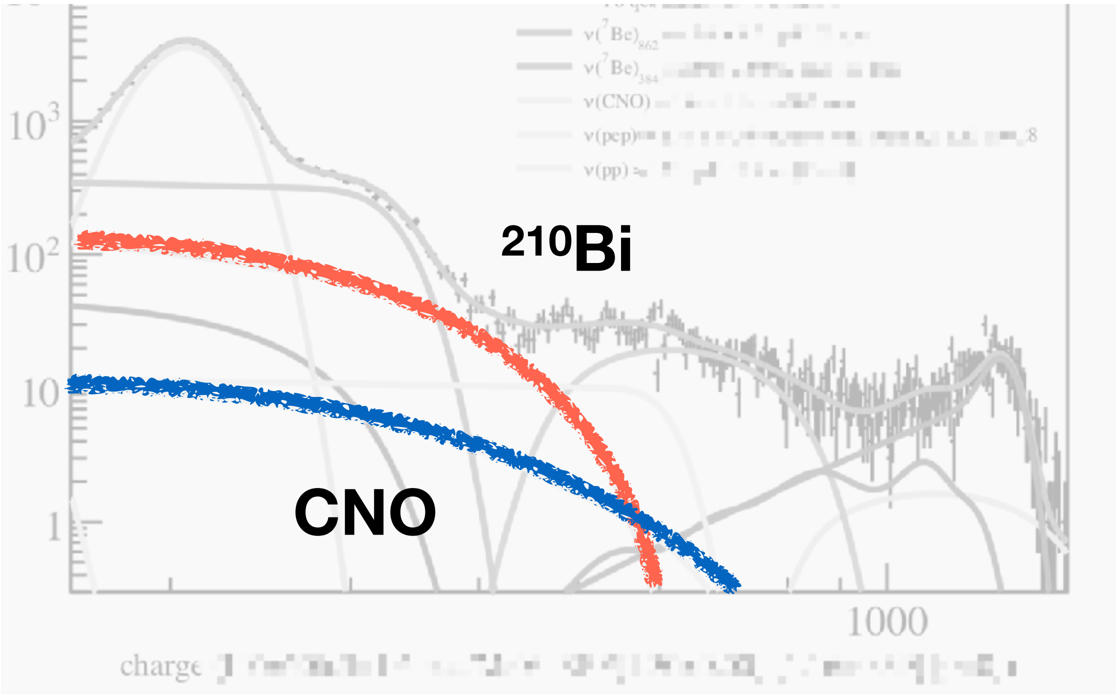
- Discriminators for models building ν mass
- Understand requirement for $0\nu\beta\beta$ experiment
- Reduce uncertainty on δ_{CP}
- Help to understand core-collapse supernovae
- Needed by absolute neutrino mass measurement

[ch10] Why ^{8}B solar ν with JUNO?

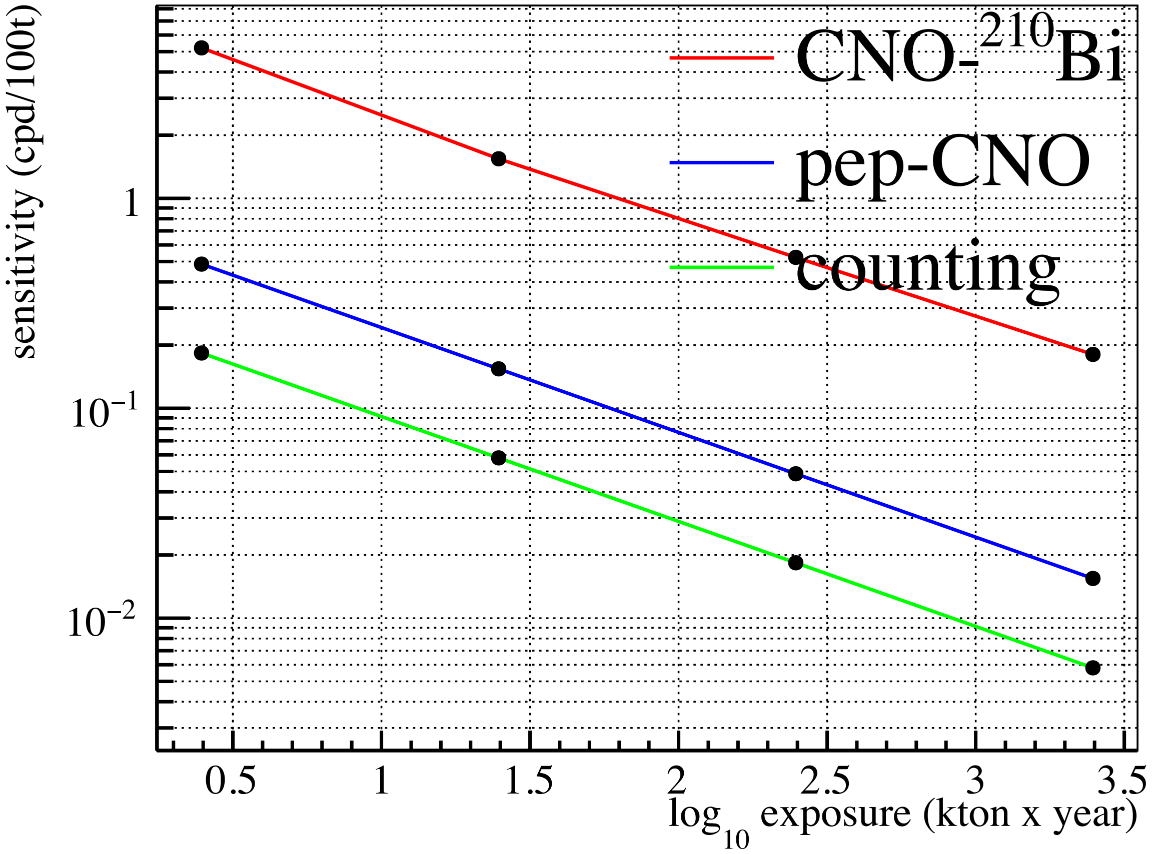
- Only a few experiments can measure ^{8}B solar neutrinos:
- **Borexino**: too small.
- **SuperK**: high detection threshold (~ 3 MeV). Cannot measure the part that is in the transition region.
- **SNO**: they think solar neutrinos are not as important as neutrinoless double-beta-decay and they can wait.
- **JUNO**: 2 MeV detection threshold. ROI: **2~3 MeV**

[ch11] CNO solar neutrinos with JUNO

- CNO solar neutrinos: similar shape with background ^{210}Bi
- Weak sensitivity on R(CNO) - R(^{210}Bi), but **improves as $\sqrt{N}$**
- When energy scale is wrong, **CNO<->^{210}Bi** can be converted. Thus the sensitivity coming from large exposure **spoiled by systematic uncertainty**.

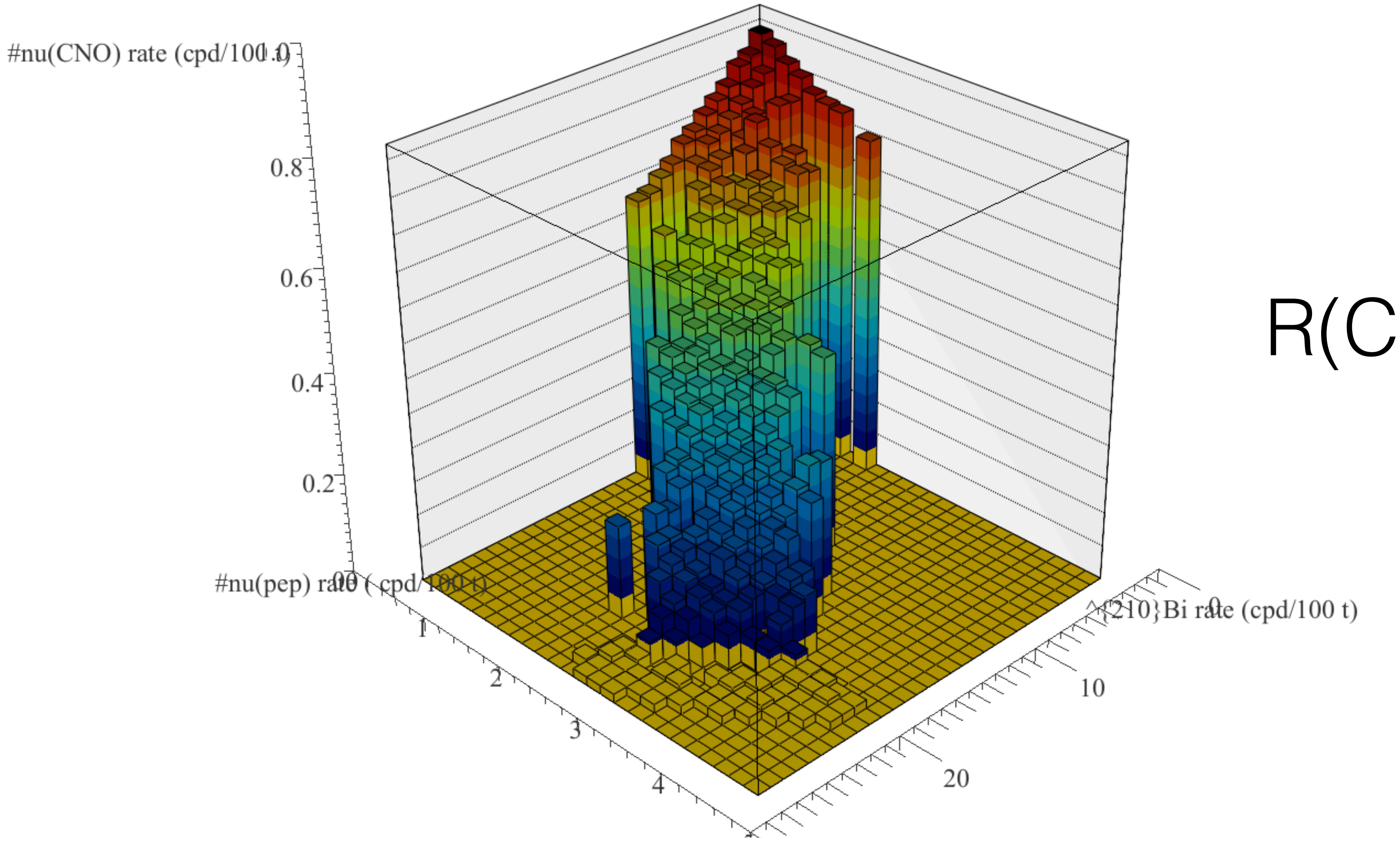


^{210}Bi vs CNO: similar shape



[ch 7] CNO: toy Monte Carlo method

- sum of CNO+^{210}Bi+pep from fit is precise
  - Maybe this sum is the count of events in some region?

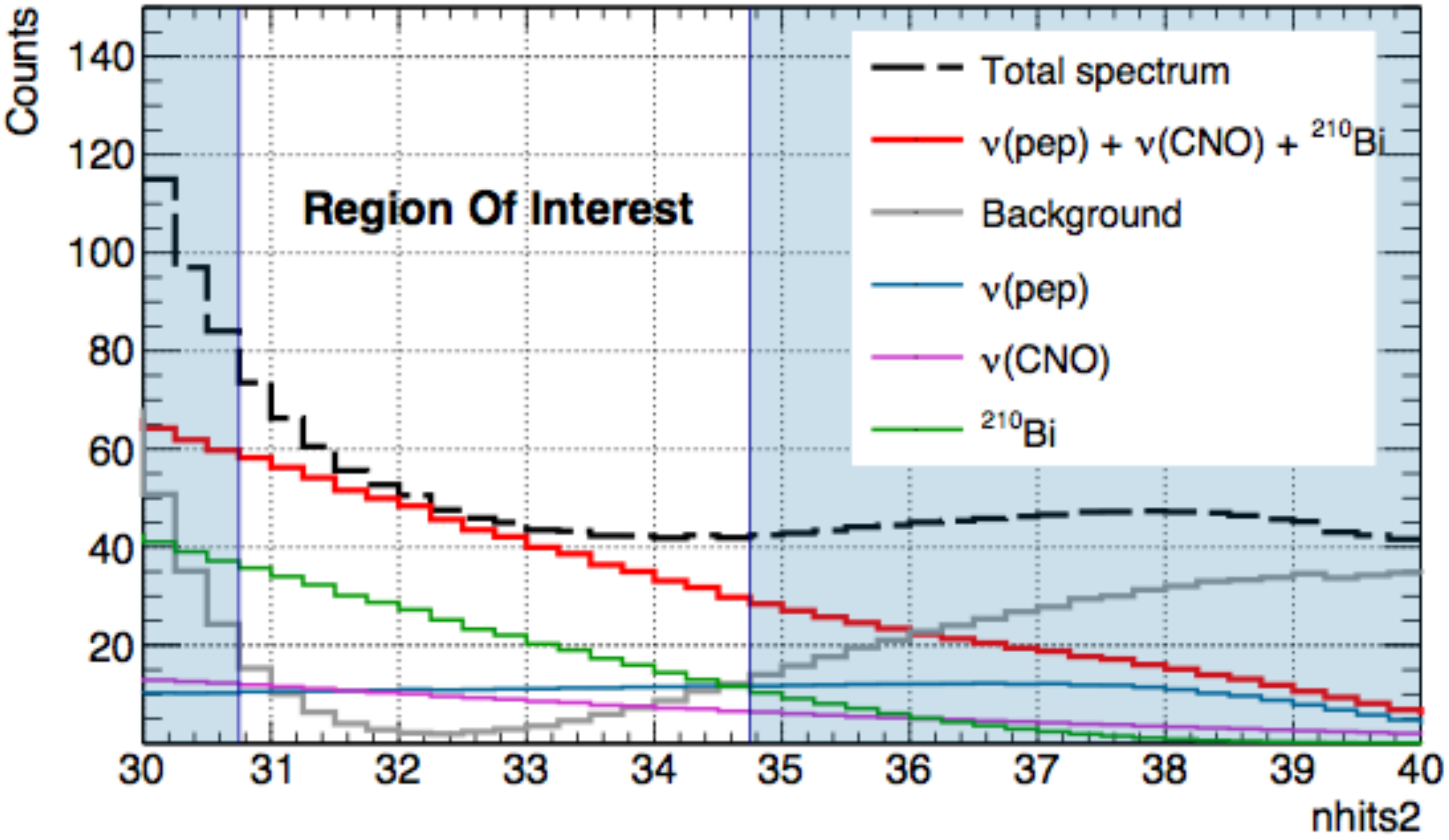


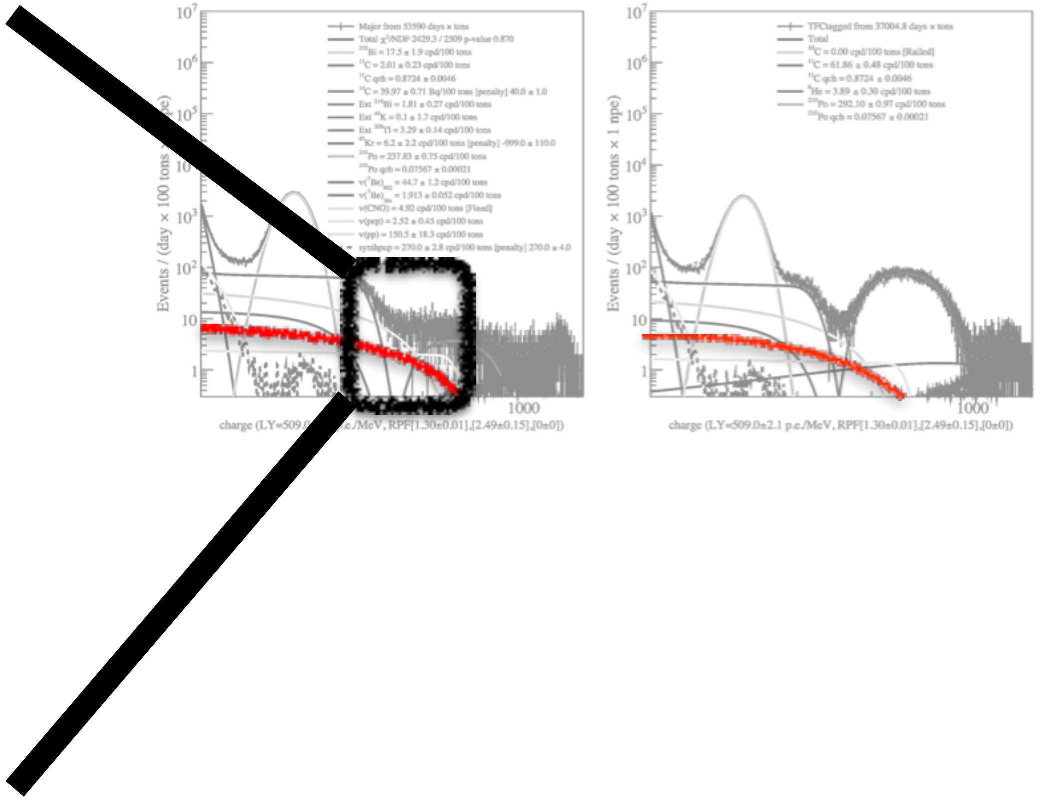
R(CNO) + **0.6** R(^{210}Bi) + **2.5** R(pep)…

We only know precisely the sum of CNO, ^{210}Bi and pep

[ch 7] CNO: counting analysis

- If we pick a region where CNO+^{210}Bi+pep dominate..





$$R(CNO) + \mathbf{0.6}\, R(^{210}Bi) + \mathbf{2.2}\, R(pep) + \text{negligible..}$$